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High-resolution reconstruction of drought episodes during the Dalton Solar Minimum (1790-1830) in the Spanish Mediterranean Basin

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ABSTRACT.

Drought is a common climate risk in the Mediterranean region, but in connection to climate change, its frequency and severity are predicted to increase during the next century. In order to better manage future scenarios in which global warming will be superimposed to natural climate variability, the nature of droughts before industrial times should be analysed in depth. This approach takes into account a broader time scale to the study of severe droughts, allowing the identification of lower frequency droughts that happened before the instrumental period. The objective of this study is to analyse the occurrence and magnitude of the extreme droughts, with durations of more than a year, in Spain during the Dalton Solar Minimum period (1790-1830). To achieve this objective, the study takes into account the use of instrumental observations and information obtained from historical documentary sources from daily to monthly resolution. The results reveal that drought episodes were more frequent and severe during the Dalton Solar Minimum period than during the second half of the nineteenth century. Furthermore, drought episodes of similar severity were hardly seen throughout the twentieth century. Only in the current context of climate change, for the last two decades, a similar pattern of high drought severity has been identified that resembles the severity found during the Dalton Solar Minimum period (especially between 1812 and 1825). This study highlights the presence of a high variability in drought patterns during the last centuries, justifying more efforts of research on drought episodes at high temporal resolution for long time periods.

KEYWORDS.

Dalton Solar Minimum, Documentary Sources, Droughts, Drought Indices, Meteorological records, Mediterranean Basin.

1. INTRODUCTION

Drought is a climate phenomenon defined as a prolonged absence of precipitation that can last for a few weeks to periods of up to several years (IDMP, 2022). Despite their complexity as a natural phenomenon, droughts should not be confused with aridity, desertification or other related natural risks such as forest fires or heatwaves (IDMP, 2022; Van Loon, 2015). Drought, as a prolonged lack of precipitation, can be classified depending on the impacts on the environment and society resulting in distinct types of drought such as meteorological, hydrological, agricultural and social (Wilhite & Glantz, 1985).

Meteorological drought is defined as a prolonged period of precipitation deficit, for a large region and for a long period of time (Mishra & Singh, 2010). This prolonged absence of precipitation is transmitted to the hydrological system by affecting soil moisture and groundwater input, ultimately reducing surface water levels (Van Loon & Van Lanen, 2012). Thus, hydrological drought is defined as a deficit in water availability that shows up in the terrestrial phase of the water cycle (Nalbantis, 2008) and has effects on groundwater and surface hydrology (Mishra & Singh, 2010; Wilhite & Glantz, 1985). This deficit causes a reduction in water supply to plant roots and consequently has a direct impact on agriculture as it leads to reduced yields and even crop failure (Mishra & Singh, 2010; Van Loon, 2015). Thus, agricultural drought depends on the evapotranspiration demand of the crop, along with the capacity of soil moisture to meet this demand (Sivakumar, 2011a). Social drought is related to the impacts on society caused by a prolonged drought over time that brings together the other types of drought (Van Loon, 2015). It refers to the social impacts of drought, which are transmitted in the form of shortages or limitations in the availability of the water resource and the failure of water supply for different uses, such as the deterioration of agricultural production, the decrease in energy or industrial production, problems in the supply of drinking water, or limitations in any recreational or ornamental use of water (Eslamian, et al., 2017; Mishra & Singh, 2010).

Due to the nature of the used data, this paper will deal with the impacts caused by meteorological drought. The sources used will be discussed in greater depth later on, but it is worth highlighting that the main inputs that make up the analysis of droughts in the historical period are the instrumental precipitation series of Barcelona (Catalonia, NE Spain) and the historical data of rogations (Spain, with higher density for Catalonia). The case of the rogations differs from that of the instrumental series, since the former focuses on the lack of precipitation while the rogations would allow the analysis of agricultural drought (Brázdil et al., 2018). However, due to the daily level of detail of the rogation system as a source of information (Martín-Vide & Barriendos, 1995), they would also allow meteorological monitoring of the natural phenomenon, since the system itself is interrupted when an improvement in rainfall is detected. The very etymology of the rogations (*pro pluvia*, to make rain) demonstrates the meteorological nature of the ceremony. Their purpose was not directly to obtain a large harvest, but only to achieve a good rainfall episode.

All the type of droughts can be characterised by several aspects; (1) severity (i.e., expressed through the own pluviometric values and through ceremony levels of *pro pluvia* rogations), (2) duration (i.e., from onset to end) , (3) spatial extent (i.e. area of impact) and (4) frequency of occurrence (Nalbantis, 2008). Long droughts can cause serious hydrological imbalance gradually increasing in severity (Wilhite & Glantz, 1985). While magnitude, duration and recurrence are necessary drought features to assess the

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physical impacts of droughts on a territory, the vulnerability of the society in relation to degree of exposure and strategies to cope with the physical hazard are fundamental for a comprehensive evaluation of climate risk. Beyond contributing to direct water scarcity, droughts affect agriculture, hinder the use of watermills and related economic activities and may aggravate political tensions connected to water rights (Gorostiza et al., 2021). Moreover, the socio-economic impacts of drought generally persist even when the episode of meteorological or hydrological drought ends and the rains return with regularity (IDMP, 2022).

Despite the importance of droughts and their capacity to seriously affect the economic and productive activities of societies, the level of knowledge on this natural phenomenon contrasts with that of other natural hazards (Van Loon & Van Lanen, 2012). Furthermore, the available knowledge focuses on very specific aspects during the instrumental period, such as the search for indices that enable little more than their classification and analysis on a natural phenomenon level (Van Loon & Van Lanen, 2012). All these reasons justify a more detailed and systematic study of droughts, as well as the analysis of specific episodes of lower frequency and greater severity which may provide additional information (Olcina, 2001a). Of particular interest are those that have occurred within the framework of the Mediterranean, where drought is an intrinsic phenomenon of the climate characteristics of the region (Olcina, 2001b).

The Mediterranean climate is characterised by a high irregularity of precipitation, both inter and intra-annual regimes, and a distinct summer (warm season) aridity (Martín-Vide & Olcina, 2001; WMO, 2023). Together with summer, winter is also characteristic for being a season with a small precipitation input. For this reason, spring and autumn are the key seasons that balance the annual water input. Strong droughts occur when the summer and winter lack of precipitations connect due to an extraordinary lack of rainfall on the rainy seasons. These seasonal aspects determine a high temporal variability of the water reserves (Kim & Raible, 2021). In addition, the high vulnerability to water availability characteristic of the Spanish Mediterranean Basin, is magnified by the major impacts sometimes caused by drought episodes (González-Hidalgo, et al., 2018). In this regard, together with drought, water management in the Mediterranean region have always been a challenge, but now it is exacerbated within the context of climate change (Hohenthal & Minoia, 2017). Additionally, serious problems have derived from greater water demands in result of population increase and the spread of a lifestyle model based on mass consumption of goods and services (IDMP, 2022). In this respect, the Mediterranean region is a clear example of imbalance between water demand and water availability. For these reasons, in recent decades, it has become one of the most sensitive areas impacted by climate change. Along with the already detected temperature increase, since the beginning of the 21st century there is also the added problem of increased precipitation variability (Barrera-Escoda & Cunillera, 2011). In this context, together with the increased precipitation irregularity, prolonged dry periods occur with greater frequency and severity (Marcos-García, et al., 2017; Kim & Raible, 2021). Therefore, drought in the Spanish Mediterranean Basin is one of the natural risks with the greatest impact, due to its capacity to cause simultaneous effects on different levels: environmental, economic, social, etc., and also its capacity to last for long periods of time (Walker et al., 2010).

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Because of the impacts of extreme hydrometeorological phenomena in the Mediterranean, such as droughts and floods, it's justified the observation of their behaviour in the recent past. It is paramount to improve the knowledge of drought natural variability on longer time scales than the instrumental period to study drought return periods on centennial scale (i.e. lower frequency) and the duration and magnitude of past extreme droughts (note that only a handful are available during the instrumental period). In the case of droughts, it is crucial to know those episodes that occurred in the past and whose severity, extent and duration were exceptional (Gil-Guirado, et al., 2016).

According to all the reasons exposed above, in the current article we will discuss on the topic of the extreme droughts that affected the Mediterranean Basins of the Iberian Peninsula during the period between 1790 and 1830, known as the Dalton Solar Minimum period. The detailed study of drought episodes during this period is justified for two main reasons: On the one hand there are the physical and social reasons that underline the exceptionality of the droughts occurred during this period. The severity of the different droughts recorded, their cumulative duration and the impact they had on the societies of the Spanish Mediterranean Basins, do not have an equal magnitude in the recent collective memory. On the other hand, this period has been studied relatively well, thanks to climate reconstructions for the beginning of the nineteenth century based on natural and historical *proxy* data and the first instrumental meteorological series (Brönnimann et al., 2018b; Prohom et al., 2016).

1.1. Research background

The Dalton Solar Minimum (hereafter, DSM) (1790-1830) occurred during the climate episode named as the Little Ice Age (hereafter, LIA) between the fourteenth and nineteenth centuries (Grove, 1988). This climate oscillation was clearly characterised by lower average temperatures with respect to the previous episode (Medieval Warm Period) and the subsequent episode (Current Global Warming) (Fischer et al., 2007). Another significant aspect of the LIA is the irregular behaviour of precipitation, with a clear increase in the frequency and magnitude of severe hydrometeorological events (Barriendos et al., 2019, Oliva et al., 2018). In the case of the Iberian Peninsula, different oscillations were observed including increases in torrential rains or droughts throughout this period (Barriendos, 1996). One of the most exceptional oscillations is called Maldà Oscillation, which occurred between 1760 and 1800 (Barriendos & Llasat, 2003). The Maldà Oscillation was characterised by simultaneous increases in the frequency of torrential rain events, alternating with droughts. The alternation of extreme precipitation and droughts events had strong social and economic impact on the Iberian Peninsula. Specifically, the sequence of droughts, cold snaps and snowfalls had serious direct consequences on agriculture, while consecutive floods also damaged or destroyed many infrastructures. Furthermore, during the period of the Maldà Oscillation there was an emergence of uncommon epidemic diseases, such as smallpox or yellow fever viruses, occurring at the same time than more common diseases such as epidemic malaria or typhoid (Barriendos & Llasat, 2003; Alberola, 2010; Alberola & Arrioja, 2018).

Within the LIA, the DSM was characterised by an abnormally low amount of emitted solar radiation, which generated an overall decrease in the amount of solar radiation arriving to the Earth (Prohom et al., 2016). In addition to this external forcing factor, climate variability at the end of the LIA was also affected by a sequence of large explosive volcanic eruptions (Wagner & Zorita, 2005; Prohom, 2003): *Unknown* (1808), Tambora (1815), Galunggung (1822) and Cosigüina (1835) (Table 1). Some studies indicate that the high intensity volcanic eruptions, occurring between the LIA and the current Global Warming, led to a decrease in temperatures, together with an increase in rainfall irregularity in the study area (Gil-Guirado et al., 2020).

Volcano	**Latitude**	**Longitude**	**Date of eruption**	**DVI***	**VEI****
Unknown	Tropical	?	c.1808/ 1810 ?	1500	6
Tambora	8ºS	118ºE	April 1815	3000	7
Galunggung	7ºS	108ºE	October 1822	500	5
Cosigüina	13ºN	88ºW	January 1835	4000	5

Table 1: Major volcanic eruptions in the period of study.
Own elaboration based on Lee & MacKenzie (2010) and Prohom et al. (2003).
***DVI: Volcanic Dust Veil Index (measure the amount of material dispersed into the atmosphere).**
****VEI: Volcanic Explosivity Index (measure the explosiveness and volume of products of volcanic eruptions).**

Among the three eruptions of the DSM, the 1815 Tambora eruption is considered one of the most significant of the past two thousand years in terms of the particles emitted, and as the cause of the more pronounced climate anomaly of the first third of the nineteenth century (Brönnimann et al., 2018b). Due to his outstanding volcanic explosivity (VEI 7) (Table 1), this eruption was the largest and most devastating eruption recorded in the historical age and is considered to be responsible for the "year without a summer" of 1816 reported across Europe and North America (Pfister & White, 2018). The regions where the effects of this "year without a summer" were most visible were mainly those of Central Europe, Western Europe and Northern Europe, with temperatures recorded of between 2 to 3ºC below the average in areas of Spain and Portugal (Pfister & White, 2018). During that summer the number of rainy days almost doubled and cloudy days were more frequent in the whole of Europe and North America. Alterations in the usual general atmospheric circulation pattern and its centres of action were also reported as a result of cooling due to the direct effect of the reflection of incident radiation associated to the presence of volcanic aerosols (Brönnimann et al., 2018b).

1.2. State of the Art of Historical Droughts Studies

Droughts analysed in their historical dimension is a subject that is part of the specialisation of historical climatology. This branch of paleoclimatology uses historical documentary sources in order to reconstruct and interpret the climate of periods for which instrumental meteorological records are scare or non-existent (Brázdil et al., 2018; Gil-Guirado, 2013). Outside of the Anglo-Saxon and Central European area of research, and particularly in the Mediterranean area, there are very few studies on extreme hydrometeorological episodes that includes an historical dimension (Kim & Raible, 2021).

The analysis of historical droughts in Spain dates back to studies by Manuel Rico y Sinobas in the mid-nineteenth century. This scientist analysed the agricultural impacts of drought episodes, and his main objective was to compile records in order to obtain a broad temporal dimension of the phenomenon (Rico y Sinobas, 1851). Subsequently, and until the beginning of the 1990s, only sporadic studies were carried out that were in some way related to events (Bentabol, 1900). One exception is the study by Couchoud (1965), who analysed in depth the region of Murcia (SE Spain) based on a detailed compilation and analytical process. In 1994, two doctoral theses on historical climatology that engaged with droughts were defended in Spain (Barriendos, 1994; Sánchez Rodrigo, 1994). They constitute benchmark studies in the research on this topic. From this decade onwards, there has been a proliferation of studies and publications in which drought is taken into consideration (see, among other, Sánchez Rodrigo, et al., 1994; Martin Vide & Barriendos, 1995; Sánchez Rodrigo, et al., 1995; Barriendos, 1997; Barriendos & Martin Vide, 1998; Sánchez Rodrigo, et al., 1998), including manuals on natural risks (Olcina, 2001a). More recently, a new doctoral thesis (Gil-Guirado, 2013) once again insisted on the need to study historical droughts in the Spanish Mediterranean Basin based on a quantitative approach.

1.3. Objectives

The main objective of this study is to analyse the patterns of drought episodes that affected the Spanish Mediterranean Basin during the Dalton Solar Minimum between 1790 and 1830 using instrumental and historical sources. This period that corresponds to the last stages of the Little Ice Age was chosen due to severity of drought occurring in the Mediterranean Basins of the Iberian Peninsula. Additional objectives of this study are: 1) to qualitatively and quantitatively extend the AMARNA database on climate risks (*Arxius Multidisciplinars per a l'Anàlisi del Risc Natural i Antròpic*, from catalan: Multidisciplinary Archives for the Analysis of Natural and Anthropogenic Risk) to incorporate droughts and different social processes linked to environmental impact in addition to hydro-meteorological excesses (Tuset et al., 2022); 2) to compile and describe the variability of extreme hydrometeorological events (torrential rainfall and droughts) in the Spanish Mediterranean Basin during the DSM; 3) to characterise the drought episodes, analysed from historical data and the instrumental precipitation series of Barcelona, considering their duration, extension and severity in high resolution for the period analysed; and 4) to analyse the entire instrumental precipitation series of Barcelona spanning from X to Y in order to characterize periods of drought.

In order to fulfil these objectives, the paper analyses the historical and instrumental data available in the Spanish Mediterranean Basins, using different time and spatial scales. The socio-environmental context during the DSM is analysed using data compiled from historical documentary sources, namely the records of the *pro pluvia* rogation ceremonies held in the main villages of the affected regions. These data are compared with the analysis of the instrumental precipitation series of Barcelona (1786-2022) based on different statistical techniques, including the use of three drought indices: SPI (McKee et al., 1993), SPEI (Beguería et al., 2010) and Deciles (Gibbs & Maher, 1967).

The article focus on analysing climate variability during the DSM period and provide the state of the art on droughts in historical perspective in Spain and Europe as a whole. Subsequently, the results obtained are presented through graphic and cartographic resources.

2. MATERIALS AND METHODS

2.1. Sources of information

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The first part of the study, based on the analysis of historical data on droughts in the Spanish Mediterranean Basin during the DSM period, has been carried out using information compiled from documentary sources of public administrations and ecclesiastical institutions. These historical data are drawn from the AMARNA database (Barriendos & Barriendos, 2021; Tuset et al., 2022). This database catalogues and classifies into numerical categories the information on a daily scale, drawn from different documentary sources. This is done by assigning geo-referencing and case and episode codes, which allows a more efficient analysis of the data.

The information compiled refers basically to water excess (persistent rainfall, pluvial and fluvial floods) and rainfall deficits (droughts). The former are obtained from administrative and private documentary sources, with direct descriptions of events and their impacts. Water deficits are obtained from the records of "*pro pluvia*" rogation ceremonies (cultural-historical proxy) drawn from municipal and ecclesiastical sources (Brádzil, et al., 2018).

With regard to the use of rogations as a source of climatic information, its main characteristic is that they are generated and initialled by public authenticators in collegiate administrative bodies (municipal councils, cathedral councils), which guarantees the reliability of the document itself and the veracity of the information contained therein. The institutional documentary sources also provide systematic and continuous records over time throughout the existence of the institution, with resources and conditions that favour the conservation and access to the documents (Martín-Vide & Barriendos, 1995; Brönnimann et al., 2018a). As a complement to these administrative sources, private personal sources have also been used, such as appointment books, memoirs or chronicles.

The rogations are the main *data proxy* in order to identify and compile information on droughts in the Spanish Mediterranean Basin. The rogation records contain reliable and homogeneous information due to their institutional origin and the formal rigidity of the related liturgical procedures (Brádzil, et al., 2018). The documentary record of the rogation ceremony informs of the location, the date and duration of the drought conditions. With respect to the severity of the event, the application of a specific methodology based on the type of liturgical acts used enables their classification by categories and their numerical indexing (Martín-Vide & Barriendos, 1995; Barriendos, 1997).

Rainfall excesses are also found in the same administrative documentary sources as the deficits and their cataloguing and numerical classification procedure is also based on objective indicators. In the 1990s, simple and extrapolatable classification criteria were proposed for all of the European basins, based on the levels of river overflows and the damage recorded (Barriendos & Martín-Vide, 1998; Brázdil et al., 1999). The first studies that used these information sources in the area of study sought to conduct an overall reconstruction of the climate variability through the generation of weighted annual indices (Barriendos, 1996; Barriendos, 2005). Subsequent studies extended the analysis with annual indices for different locations of the Spanish Monarchy, both on historical floods (Barriendos & Sánchez Rodrigo, 2006) and for droughts (Domínguez-Castro et al., 2008; Domínguez-Castro et al., 2012; Sánchez Rodrigo & Barriendos, 2008, Tejedor et al., 2019; Gil-Guirado, et al., 2019).

In addition to the analysis of historical data, the second part of the study consists in the statistical analysis of the instrumental precipitation series of Barcelona (1786-2022). The series has been compiled by consulting different documentary sources and different series of records. The principal source is the one elaborated by the *Servei Meteorològic de Catalunya* (SMC) (Prohom et al., 2016), complied by different institutional observers who generated records from the eighteenth century. The analysis of these sources has enabled the homogenisation of the monthly precipitation series from 1786 to 2014. To complete the SMC series up to the year 2021, instrumental records from a private observatory in the Can Bruixa neighbourhood of Barcelona have been accessed. In addition, to cover the year 2022, we have accessed the official SMC data from the Raval automatic station (University of Barcelona).

2.2. Indexation system of historical climate data

This study is based on the use of information on a daily scale drawn from historical data. Therefore, it has been necessary, in the first phase, to catalogue and classify the information on rainfall deficits. To do this, the methodological procedure used for analysing floods in the PREDIFLOOD and MEDIFLOOD databases has been followed (Barriendos et al., 2014; Barriendos et al., 2019). These databases resulted from the R+D+I projects PREDIFLOOD (PI: Dr. Carles Balasch, University of Lleida, 2013-2015) and MEDIFLOOD (PI: Dr. David Pino, Polytechnic University of Catalonia, 2016-2019), which, through multidisciplinary teams, compiled and analysed information on historical floods in the area of Catalonia and, in a complementary way, the whole of the Mediterranean basins of the Iberian Peninsula. The research teams of the above-mentioned projects defined a much more comprehensive and enduring cataloguing and classification structure under the name AMARNA (*Arxius Multidisciplinars per a l'Anàlisis del Risc Natural i Antròpic,* translated into english as Multidisciplinary Archives for the Analysis of Natural and Anthropogenic Risk). This structure enables the cataloguing and classification of any type of extreme meteorological event and its social impacts. The total number of records for the period EC 1035-2022 amounts to slightly more than 19,000 cases, organised in more than 5,500 episodes (Tuset et al., 2022).

Accessing this database and its archive of original materials has enabled the tasks of cataloguing and classifying large amounts of information to be undertaken on a daily scale. The information on water excesses has already been organised(Barriendos et al., 2014). Based on this precedent, this research is focused on drought and other convective and thermal atmospheric events, together with the impacts on the social system, such as famines, plagues or epidemics (Barriendos & Barriendos, 2021).

The information currently managed by AMARNA has evolved substantially since its creation in 1994 (Barriendos, 1996). It is organised into episodes that group the records of different dates and locations, providing information about the scope and duration of each episode. After being catalogued, the information was classified into five categories and fifteen sub-categories which are currently being developed (Barriendos & Barriendos, 2021) in order to cover all types of information that can contribute to the knowledge of extraordinary atmospheric behaviours (Barriendos & Barriendos, 2021). The fifteen thematic subdivisions proposed correspond to the maximum detail that it is possible to identify in the documentary and bibliographic sources consulted (Table 2).

CATEGORIES		SUB-CATEGORIES	
Code	**Name**	**Code**	**Name**
ERE	Extraordinary Rainfall Event	FF	Fluvial Flood
		PF	Pluvial Flood

		PR	Persistent Rainfall
		SS	Sea Storm
		DR	Drought
ECE	Extraordinary Convective Event	HE	Hail Event
		ES	Electric Storm
		WS	Wind Storm
ETE	Extraordinary Thermic Event	CW	Cold Wave
		US	Unusual snowfall
		HW	Heat Wave
SIE	Social Impact Event	EE	Epidemic Event
		PE	Plague Event
		FS	Food Shortage
ERR	Technical mistake	ERR	Spurious case

Table 2: Classification system of the AMARNA database.

For the case of the extreme hydrometeorological events, such as floods, different classification systems are initially developed which combine hydrological characteristics and social impacts. There is a first classification development with categories of three levels (Barriendos & Martin-Vide, 1998) and a subsequent improved development that contemplates five levels (Barriendos et al., 2014). The new classification system enables the quantification of the episodes, differentiating their variables: hydrological, structural and human (Tuset et al., 2022). For the rainfall deficits, the classification system based on the *pro pluvia* rogations is still used, which provides between three and five levels of severity according to the vulnerability of the populations studied. These categories are based on objective criteria provided by the formality of the liturgical ceremonies used (Martin-Vide & Barriendos, 1995).

Finally, through the georeferencing of all the historical information of the database, SIG tools have been used for their cartographic representation. On the one hand, the distribution of the droughts in the Dalton Solar Minimum period have been represented both on a municipal level and with the cases grouped by hydrographic basin. The hydrographic basins are the Spanish administrative units for managing water resources (Table 3) (MITECO, 2023). On the other hand, the spatial-temporal distribution of the impacts used by different drought episodes representative of the period of study has been analysed.

Basin Code	**Basin Name**	**Watershed (Sea)**	**Area (km^2)**	**Area (%)**
CIG	Galicia Coastal Rivers	Atlantic Ocean	367,464	65.9%
NOR	Northwest (Miño River)			
COC	Northern Rivers, Western Side			
COR	Northern Rivers, Eastern Side			
CHD	Duero River			
CHT	Tajo River			
CGN	Guadiana River			
CAA1	Andalucia Atlantic Rivers (Guadalete+Barbate)			
CAA2	Andalucia Atlantic Rivers (Tinto+Odiel+Piedras)			
CGQ	Guadalquivir River			
CMA	Andalucia Mediterranean Rivers	Mediterranean Sea	189,928	34.1%
CHS	Segura River			

CHJ	Júcar River			
CHE	Ebro River			
CIC	Catalonia Coastal Rivers			
BAL	Balearic Islands			

Table 3: Spanish hydrographic basins analysed in this study.

2.3. Statistical analysis of the instrumental precipitation series

Different drought indices have been applied to the precipitation series of Barcelona (1786-2022). In all cases, it was decided to calculate the indices based on monthly values and for groups of 12 months. The first index used was the SPI (*Standarized Precipitation Index*) (McKee et al., 1993), a tool widely used for classifying droughts (WMO & GWP, 2016). This index enables the analysis of the duration and variability of the droughts and of the wet periods and is generated based on the transformation of the temporal precipitation series in a standardised normal distribution (Lloyd-Hughes & Saunders, 2002; Gil-Guirado & Pérez-Morales, 2019; Zargar et al., 2011). The second index is the SPEI (*Standarized Precipitation Evapotranspiration Index*) (Beguería et al., 2010). This index functions in a very similar way to the SPI index, but also using the average monthly temperature variable (WMO & GWP, 2016). It is a relatively versatile index, simple to apply and enables analyses to be carried out for any climate regime (Stagge et al., 2015). The third index used is the Deciles index (Gibbs & Maher, 1967), which stands out for its applicability and simplicity, due to the facility of the calculations that it requires and the fact that it only requires precipitation data (Hayes & Cavalcanti, 2005; Tsakiris, et al., 2007). This method is obtained by dividing the distribution of the monthly precipitation data into deciles (WMO & GWP, 2016), which define thresholds for different water deficit conditions (Eslamian et al., 2017; Zargar et al., 2011).

Once the results of the three indexes were obtained, their precipitation patterns were identified and the breakpoints of the three index series were detected. The testing of the trend of the indexes was carried out using the Mann Kendall test and with the Sen slope. The analysis of the breakpoints of the series of the monthly values of the three indices was conducted using the Pettitt Test (Gil-Guirado & Pérez-Morales, 2019).

3. RESULTS

3.1. General characteristics of data on hydro-meteorological extremes

For the Dalton Solar Minimum (DSM) (1790-1830), the AMARNA database provides 2047 cases for the whole of the Iberian Peninsula. These cases are grouped, in turn, into 708 episodes (Barriendos et al., 2019) (Table 4).

	AMARNA (1035-2022)	**AMARNA DSM (1790-1830)**
Number of episodes	5551	708
Number of cases	19115	2047

Table 4: Amount of information available in the AMARNA database.

For this period, of all the cases, 1789 correspond to ERE events (Extraordinary Rainfall Event). Within these cases, there is a clear predominance of the subcategory DR (Drought), with 64% of the ERE cases (Figure 1).

Values of ERE events		
Subcategories	**Number of cases**	**Percentage**
Fluvial Flood (FF)	431	24.09 %
Pluvial Flood (PF)	40	2.24 %
Persistent Rainfall (PR)	164	9.17 %
Sea Storm (SS)	22	1.23 %
Drought (DR)	1132	63.28%
Total	**1789**	

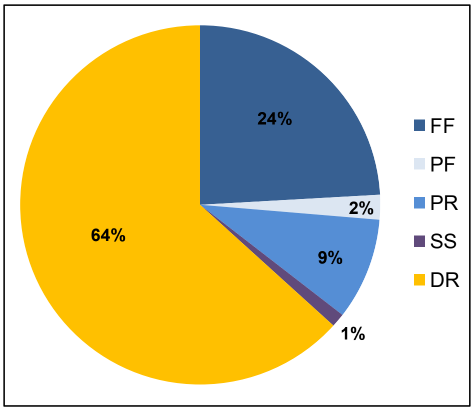

Figure 1: Total number of cases of the five groups making up the ERE category (Extreme Rainfall Event).

The temporal distribution of the ERE episodes throughout the DSM reveals a predominance of droughts with respect to the other types of ERE, but with a non-homogeneous distribution (Figure 2). For instance, in the first decade of the DSM rainfall was abundant, making floods more significant than droughts in specific years such as 1793, 1797 or 1801 (Figure 2 and Figure 3). This first decade also stands out due to its clear interannual irregularity, which can be related to the final part of an abnormal climate period detected between 1760 and 1800, known as the Maldà Oscillation (Barriendos & Llasat, 2003).

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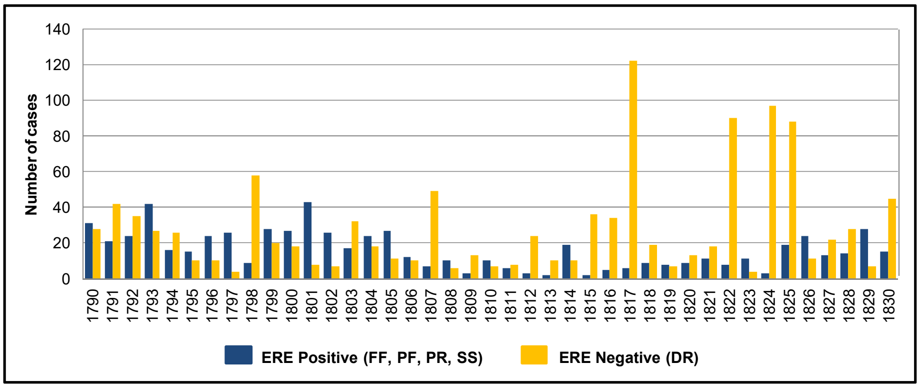

Figure 2: Temporal distribution of positive EREs and negative EREs during the Dalton Solar Minimum (1790-1830).

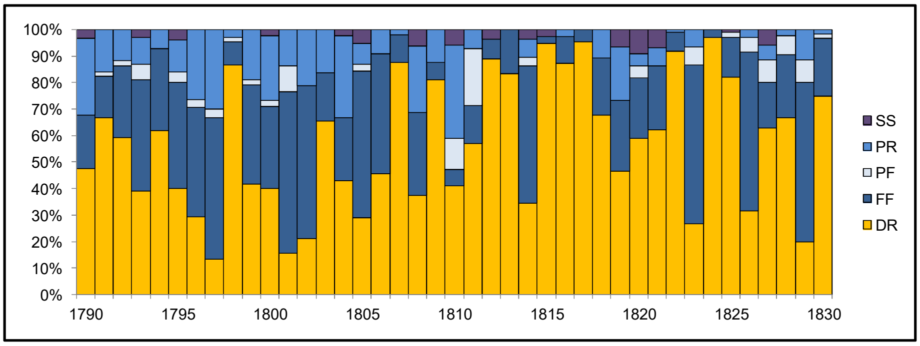

Figure 3: Temporal distribution of cases for the five groups of the ERE category during the Dalton Solar Minimum (1790-1830).

The standardised values of cases on an annual level show the most pronounced episodes of droughts and water excesses. Its temporal distribution is evident: in the first decade, positive extreme peaks were interrupted with the drought of 1798. On the other hand, from the episode of 1807, droughts became predominant, being particularly severe between 1812 and 1825 (Figure 4).

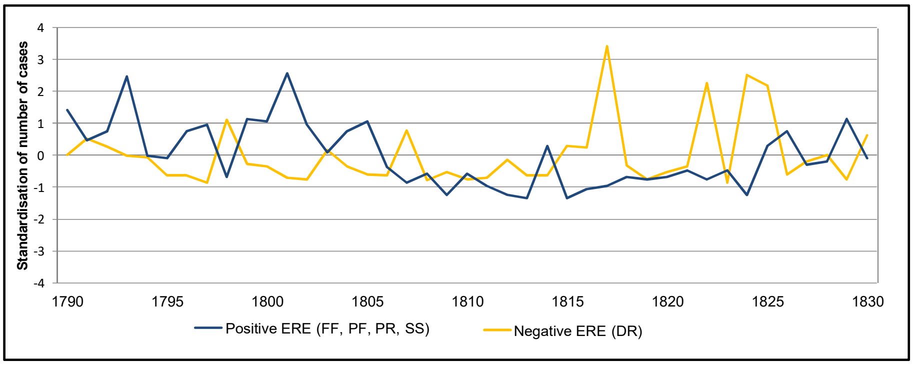

Figure 4: Annual cases of positive EREs and negative EREs during the Dalton Solar Minimum (1790-1830). Standardised values.

Two phases can be clearly observed (Figure 5): a first wet phase and then a dry phase. The positive EREs diminished from 1806 definitively for the rest of the DSM, while the negative EREs increased from 1812. Therefore, a transition period or one of relative normality can be defined between 1806 and 1812, that is, just six years for the total of the 40 analysed.

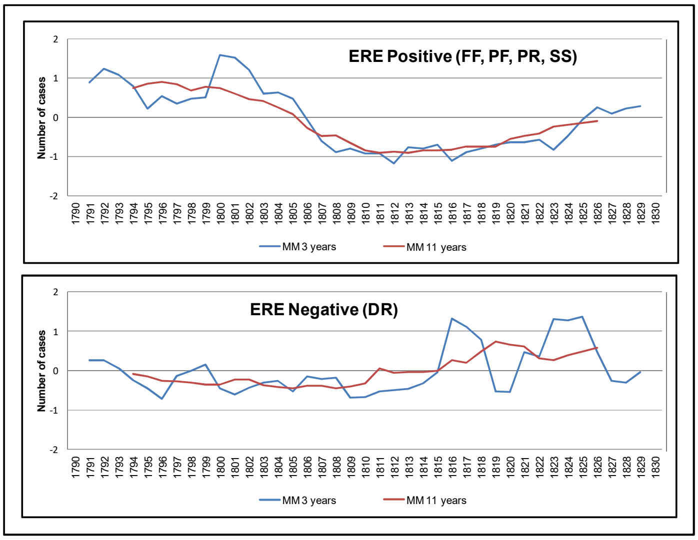

Figure 5: Moving averages of 3 and 11 years of the standardisation of the annual positive ERE and negative ERE cases for the Dalton Solar Minimum period (1790-1830).

With respect to the geographical distribution, the large number of cases recorded in the Spanish Mediterranean Basin particularly stand out with respect to those recorded in the Atlantic basin for the same period (Figure 6). The predominance of drought in the Spanish Mediterranean Basin contrasts with the greater impact of the positive ERE episodes in the Atlantic Basins. In the Mediterranean area, the Júcar basin stands out as there is a high incidence of positive ERE there, unlike the dynamics of the other Mediterranean basins. This anomaly may be due to the fact that in this basin no specific campaigns for compiling drought information have been carried out.

Basin Code	Number of ERE positive	Number of ERE Negative
CIG	18	12
NOR	1	0
COC	0	0
COR	4	5
CHD	11	19
CHT	15	24
CGN	5	0
CAA1	0	1
CAA2	0	0
CGQ	71	90
CMA	17	0
CHS	90	265
CHJ	104	4
CHE	75	177
CIC	223	518
BAL	19	15
Total	**653**	**1130**

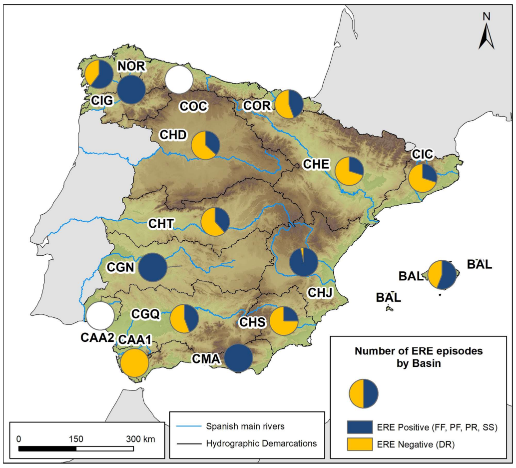

Figure 6: Number of positive ERE cases (FF, PF, PR, SS) and negative ERE cases (DR) for the different Spanish river basins. Dalton Solar Minimum (1790-1830). A list of the full names of the basin codes can be found in Table 3.

The predominance of drought in the Mediterranean Basin is confirmed when we analyse the spatial distribution of the towns that account for more than 50 cases of drought (Figure 7). Except for Seville, which is in the Atlantic watershed, the rest are located in the Mediterranean basin. With respect to the temporal distribution of the different cities, the case of Murcia is noteworthy as it is characterised by the regularity with which drought episodes occur compared to the majority of cities that exhibit a greater temporal variability (Olcina, 2001b). This fact is related to its geographical position in the region of south-east Spain. Within this environment, “specific” drought events occur (the so-called “surestinas” south-eastern droughts) related to the lack of precipitation from the Atlantic and absence of Mediterranean rainfall events (Olcina, 2001b).

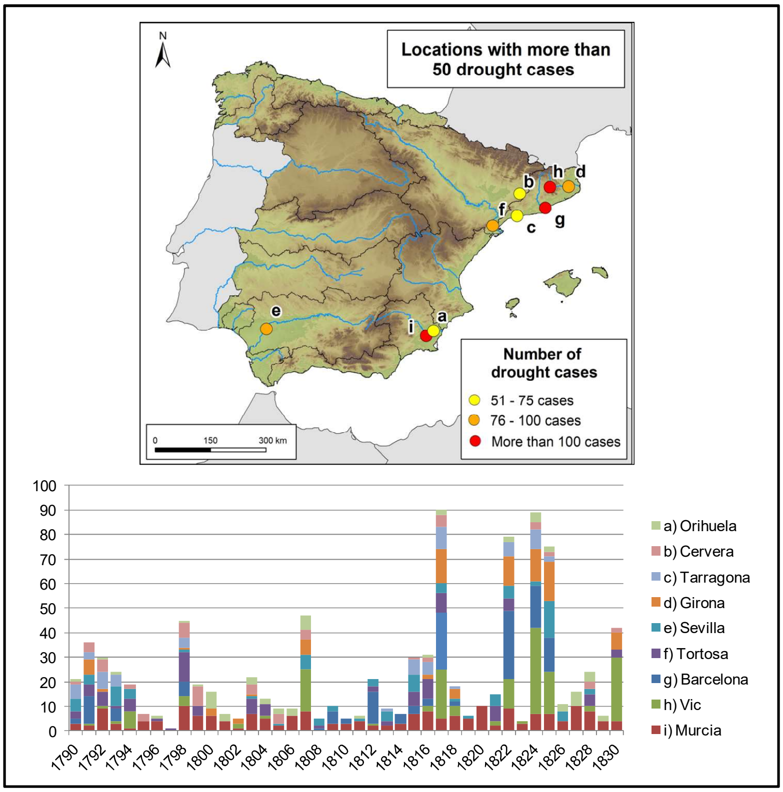

Figure 7: Towns with more than 50 cases of drought. Dalton Solar Minimum (1790-1830).

3.2. Drought analysis of the Dalton Solar Minimum period on the Spanish Mediterranean Basin

Going into a greater level of detail, using historical data, the information of some of the most severe drought episodes of the Dalton Solar Minimum can be analysed (Table 5). This section takes into account the groupings of cases occurring in specific periods of the DSM, analysing the different Spanish towns that record rogation ceremonies for each episode. In this regard, it will be possible to consider the different nuances that appear in the most representative droughts of the analysed period.

Episode	Year of greatest impact (Nº Cases)	Approximate duration	Total cases
1798 -1799	1798 (58)	25 months	78 cases
1807 -1808	1807 (49)	19 months	55 cases
1812 -1814	1812 (24)	21 months	44 cases
1816 -1818	1817 (122)	37 months	175 cases
1822 -1825	1824 (97)	40 months	279 cases

Table 5: Summary of the severe drought episodes according to historical data. Dalton Solar Minimum (1790-1830).

The first of these episodes runs from December 1797 to December 1799, with the peak of intensity in March and April 1798. This episode stands out as it occurred several years before the megadrought of 1812-1825 and was possibly an episode still linked to Maldà Oscillation (Barriendos & Llasat, 2003). It affected five hydrographic basins (Catalan basins, Ebro, Segura, Tajo and Guadalquivir), three of which are Mediterranean (Figure 8). Despite its considerable extension, this episode had a limited duration, with only a few months of rogations. The exception is the municipality of Murcia, where rogations were recorded for 10 months of the 25 that the episode lasted. Furthermore, this episode was noteworthy in Murcia due to plague outbreaks (Zamora Pastor, 2001).

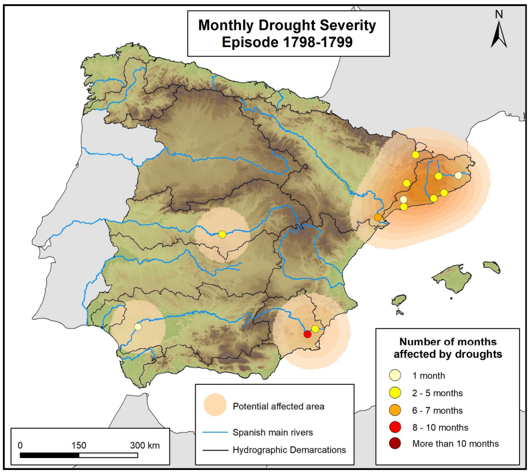

Figure 8: Distribution of *pro pluvia* rogations by municipality. Drought episode 1798-1799.

The second episode of severe drought occurred between January 1807 and July 1808 (Figure 9), with the largest number of cities holding rogations in October 1807. It affected six river basins (Catalan basins, Ebro, Balearic basins, Segura, Duero and Guadalquivir), four of which are Mediterranean. Its main characteristic is that it had a greater impact on towns in the southern sector of the Atlantic and Mediterranean watersheds of the Peninsula, such as Murcia and Seville.

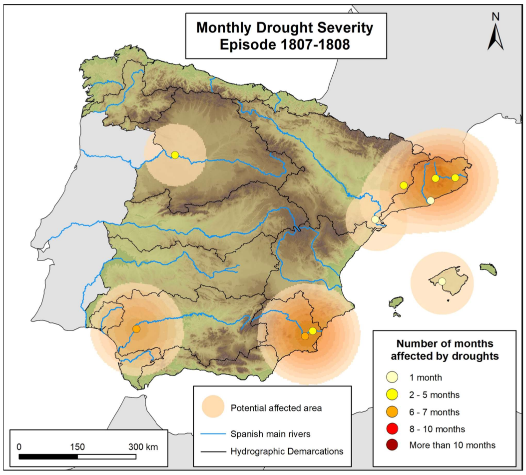

Figure 9: Distribution of *pro pluvia* rogations by municipality. Drought episode 1807-1808.

The third episode accumulated less cases of drought but marked the beginning of the megadrought that lasted until 1825, with different regional effects throughout the sequence. It occurred between March 1812 and April 1814 with the peak of greatest severity in April 1812 (Figure 10). Despite the low number of rogations recorded (44), during this drought significant effects on crops were documented, causing wheat shortages and widespread famine in the Mediterranean basins. It had a broad impact across the Iberian Peninsula, affecting eight river basins (Catalan basins, Ebro, Balearic basins, Júcar, Segura, Duero, Tajo and Guadalquivir), three of which are in the Atlantic watershed.

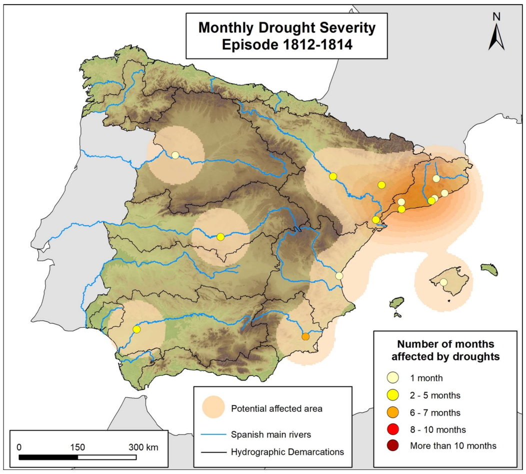

Figure 10: Distribution of *pro pluvia* rogations by municipality. Drought episode 1812-1814.

The fourth episode took place between December 1815 and November 1818 (Figure 11) and stands out for the impact of the drought during 1817, which was very severe in Catalonia with instrumental records in Barcelona that were unprecedented until that moment (Moruno, 2020). In this episode, there was an exceptionally dry month (April 1817) in which fourteen of the twenty municipalities recorded *pro pluvia* rogations. This drought affected eight very broadly distributed river basins; four Mediterranean basins (Catalan basins, Ebro, Balearic basins and Segura) and four Atlantic basins (Galician basins, Duero, Tajo and Guadalquivir). Rogations were made during this drought for many months, particularly in the cities of Murcia and Girona with 12 and 11 months, respectively.

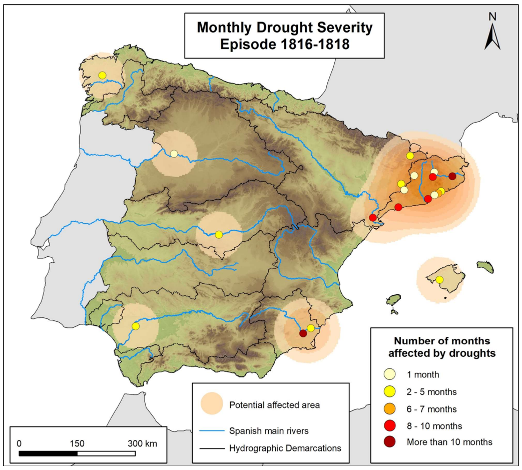

Figure 11: Distribution of *pro pluvia* rogations by municipality. Drought episode 1816-1818.

The last episode took place between January 1822 and January 1826 (Figure 12), although the year 1823 recorded a low number of rogations. This drought is noteworthy for being the longest and most persistent of the Dalton Solar Minimum period (40 months). Three different peaks of severity can be observed: March 1822, April-May 1824 and February 1825. This drought affected eight very broadly distributed river basins: four Mediterranean basins (Catalan basins, Ebro, Balearic basins and Segura) and four Atlantic basins (Galician basins, Duero, Tajo and Guadalquivir). Also significant was the large accumulation of rogations carried out each month in the towns affected. For example, the town of Vic recorded twenty months with rogations, Murcia seventeen months and Barcelona fifteen. This episode was accompanied by price increases of wheat and the emergence of a locust plague which affected different towns (Azcárate, 1996).

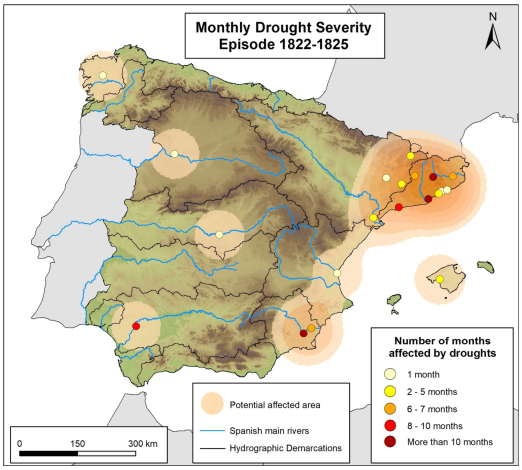

Figure 12: Distribution of *pro pluvia* rogations by municipality. Drought episode 1822-1825.

3.3. Analysis of the instrumental precipitation series of Barcelona (1786-2022)

The analysis of the instrumental precipitation series of Barcelona (1786-2022) has been carried out by applying three different drought indices (SPI, SPEI and Deciles) (Figure 13). Among the observed behaviours, the dry period of the first third of the 19th century stands out. The analysis of the series with three different indices highlights that the Dalton Solar Minimum period was significant because it concentrated the periods of greatest severity and duration of drought. The three indices also show values of relative abundant rainfall from the end of the nineteenth century until the end of the twentieth century. Finally, the beginning of the twenty-first century reveals an upturn in the severity and duration of the drought episodes with respect to the twentieth century.

The SPI, in comparison with the behaviour of the other two indices, is the one that highlights more clearly the peaks of greater severity, both positive and negative (Figure 13). In this regard, 1817 stands out as the driest year in the precipitation series, with months of maximum severity reaching values close to -4 (-3.91 in the month of August) (Table 7). Observing the results of this index, it becomes clear that after the DSM, during the 1830s, the years with drought conditions were prolonged, ending around 1840. From the mid-nineteenth century a more stable phase began with a low presence of prolonged dry periods until the end of the twentieth century. In the twenty-first century, severe drought values are being seen again. For example, in 2021, a negative value of the SPI of close to -3 was recorded for the first time since the DSM.

The SPEI shows a different result to the other two indices as it combines precipitation and temperature values. In this respect, it is noteworthy that the most severe year of the series, according to the SPEI was not 1817 but 1822. It is possible that the negative thermal effect of the Tambora eruption (1815) was still significant in 1817, resulting in 1822 having a higher temperature and, consequently, a lower SPEI value. The 1870-1890 drought episode, which does not stand out so much in the other two indices, is also perceived as severe. With regard to the 20th century, SPEI shows a phase of positive values that lasted twenty years from the 1970s to the 1990s with almost not a single month with negative values. In contrast, for the beginning of the 21st century there are hardly any years with such positive values (Figure 13). Undoubtedly, the recent thermal warming increases the intensity of negative SPEI values and presents increased problems for water management.

The behaviour of the Deciles index is very similar to that obtained with the SPI index. This index softens the extreme positive and negative behaviours. To do this, the interpretation of precipitation abnormalities does not help, with only the most evident episodes being highlighted.

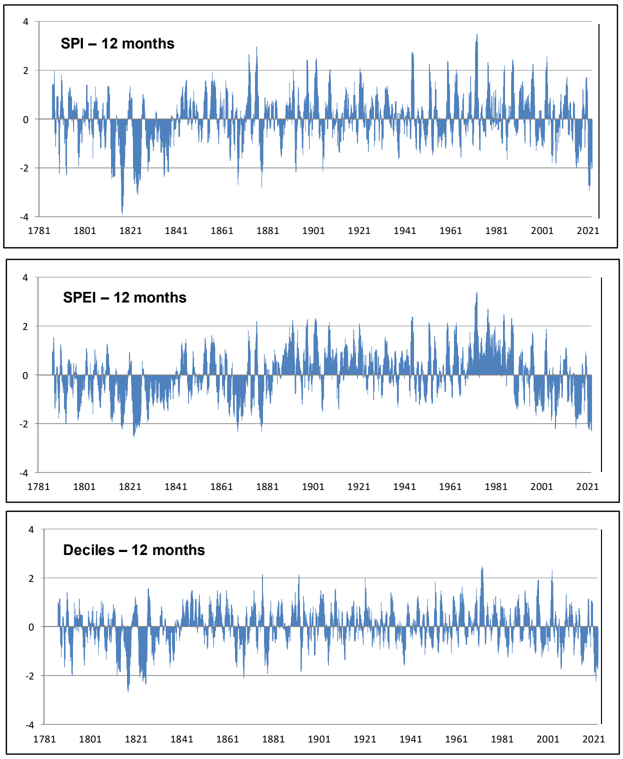

Figure 13: Monthly values of the SPI, SPEI and Decies indexes for the Instrumental precipitation series of Barcelona (1786-2022).

The moving averages of 2 and 11 years show the most persistent behaviours in the drought index series (Figure 14). This provides clusters of months that define the droughts and wet periods on a long scale. The smoothing obtained with the moving averages highlights with more emphasis the megadrought of the first third of the 19th century and its severity throughout the precipitation series. At the same time, the smoothing of the SPEI index also shows the marked positive phase of the 20th century, which ends abruptly in the 1990s with another dry period, which continues to the present day. Examining these results, it appears that the drought of the 21st century is not as intense as those of the DSM period, but may eventually become of similar duration and severity.

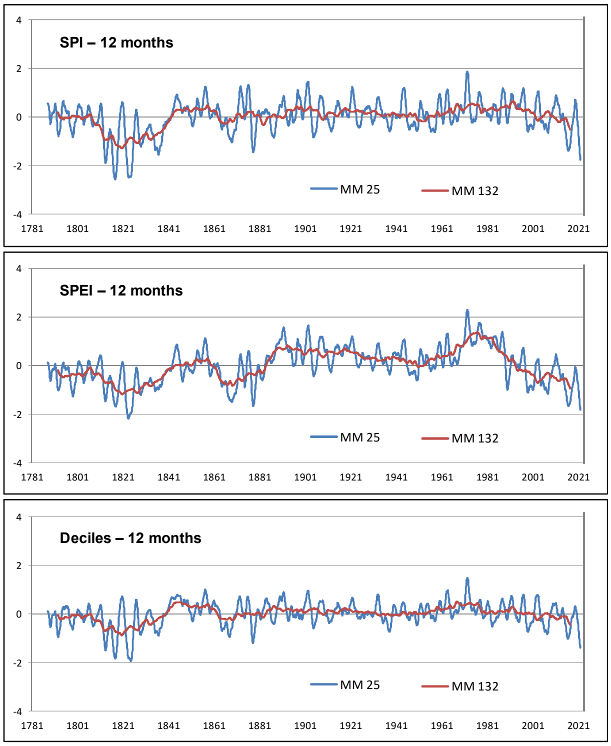

Figure 14: Moving averages of 2 and 11 years of the values of the SPI, SPEI and Decile indices for the whole of the instrumental precipitation series of Barcelona (1786-2022).

The results obtained with the Pettitt Test are very similar for the SPI and Decile index values, although there are differences with respect to the SPEI index (Figure 15 and Table 6). The principal difference is found in the position of the first breakpoint which, for the case of the SPI and Deciles, occurred right at the end of the Dalton Solar Minimum period, in the 1840s. On the other hand, for the SPEI index, this first breakpoint occurred at the end of the nineteenth century, when a strong dry period ended that had lasted from 1860 to 1880 and is much more important in this index than in the other two analysed. With respect to the breakpoint that marks the end of the wet period of the twentieth century, the SPI and Decile indices also coincide with the same period, at the end of 1997. Meanwhile, the SPEI marks it at the end of the 1980s, after the wet phase of the 1970s and 1980s. From this point, the three indices go back to indicating negative averages for their respective series (Figure 15 and Table 6).

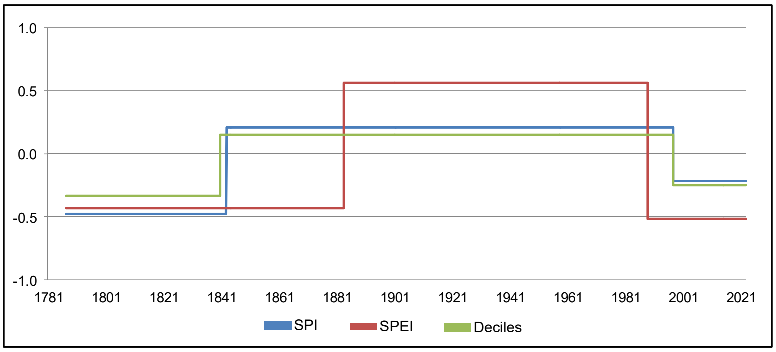

Figure 15: Breakpoints according to the Pettitt Test for the three drought indices (SPI, SPEI and Deciles).

Monthly data series	Pettitt Test Results 1rst section's average	1rst breaking point	2nd section's average	2nd breaking point	3rd section's average
SPI	- 0.48 (669 m: 56 yr)	October 1842	0.21 (1862 m: 155 yr)	December 1997	-0.22 (301 m: 25 yr)
SPEI	- 0.43 (1157 m: 96 yr)	June 1883	0.56 (1266 m: 105 yr)	December 1988	-0.52 (409 m: 34 yr)
Deciles	- 0.34 (643 m: 54 yr)	August 1840	0.15 (1886 m: 157 yr)	October 1997	-0.25 (303 m: 25 yr)

Table 6: Results of the breakpoints according to the Pettitt Test for drought indices (SPI, SPEI and Deciles).

Based on the values of the three indices, the drought episodes are summarised for the Barcelona series (Table 7). It reveals a greater number of drought episodes recorded in the nineteenth century compared to the 21st century, in which the droughts were not only scarce but also less severe and shorter (Figure 16). This is confirmed if we consider that in the first twenty years of the 21st century the same amount of droughts have been recorded as those occurring throughout the whole of the twentieth century.

The droughts of the DSM period (Nr. 2 to 8) stand out due to their extreme severity, particularly those in the central part of the period, when not only were the droughts severe but also a large number of dry months were concentrated during this time (Table 7, Figure 15). For the rest of the drought episodes of the series, we can observe that the majority had shorter durations (Figure 16). Only three drought episodes are noteworthy outside of the DSM: 1877-1879 (Nr. 14), 2015-2018 (Nr. 23) and 2021-2022 (Nr. 24).

Episode Num.	Date		Month Num. *	Averages of index values for each episode			Minimum values of the episodes **			
	Onset	Ending		SPI	SPEI	Dec.	SPI	SPEI	Dec.	Month
1	1789/09	1790/03	6	-1.34	-1.47	-1.24	-2.22	-1.79	-1.67	11/1789
2	1792/05	1793/04	12	-1.38	-1.53	-1.38	-2.29	-2.00	-2.00	01/1793
3	1798/03	1798/12	10	-1.36	-1.59	-1.02	-1.94	-1.76	-1.58	05/1798
4	1807/09	1808/04	8	-0.84	-1.09	-0.97	-1.19	-1.31	-1.33	01/1808
5	1812/05	1814/05	25	-1.88	-1.47	-1.49	-2.46	-1.82	-2.00	10/1812
6	1815/11	1818/11	37	-2.06	-1.43	-1.45	-3.91	-2.24	-2.67	08/1817
7	1822/03	1825/11	45	-2.23	-2.02	-1.75	-3.10	-2.22	-2.17	01/1824
8	1828/01	1829/05	17	-1.41	-1.46	-1.08	-2.14	-1.95	-1.58	10/1828
9	1834/04	1836/04	25	-1.35	-1.06	-0.78	-2.35	-1.44	-1.67	11/1835
10	1836/11	1837/12	14	-1.61	-1.07	-0.96	-2.17	-1.46	-1.42	08/1837

11	1864/04	1864/11	8	-1.34	-1.51	-1.11	-1.71	-1.72	-1.50	09/1864
12	1867/10	1868/10	13	-1.74	-1.94	-1.27	-2.69	-2.32	-2.08	03/1868
13	1869/10	1870/07	10	-1.18	-1.60	-0.48	-1.62	-1.86	-0.75	11/1869
14	1877/05	1879/01	21	-1.64	-1.78	-1.33	-2.80	-2.31	-1.92	08/1978
15	1886/07	1887/08	14	-1.13	0.05	-0.57	-1.60	-0.16	-0.92	03/1887
16	1893/02	1893/10	9	-1.44	-0.19	-1.22	-2.19	-0.79	-1.83	04/1893
17	1904/12	1905/10	11	-1.47	-0.99	-0.99	-2.15	-1.53	-1.58	04/1905
18	1937/11	1938/08	10	-1.26	-0.98	-1.27	-1.65	1.32	-1.50	03/1938
19	1947/05	1948/01	9	-1.07	-1.01	-0.67	-1.40	-1.23	-0.83	10/1947
20	1952/10	1953/05	8	-1.22	-1.05	-0.8	-1.49	-1.20	-1.00	03/1953
21	1965/02	1965/09	8	-1.23	-0.76	-0.52	-1.58	-0.88	-0.75	09/1965
22	2005/03	2005/09	7	-1.38	-1.57	-0.98	-1.79	-1.86	-1.25	07/2005
23	2006/11	2007/04	6	-1.28	-1.84	-1.46	-1.84	-2.15	-1.75	01/2007
24	2015/09	2018/07	35	-1.29	-1.60	-0.85	-2.00	-2.15	-1.50	03/2016
25	2021/04	2022/12	21	-2.11	-2.04	-1.6	-2.92	-2.22	-1.92	09/2021

Table 7: Drought episodes in the instrumental precipitation series of Barcelona (1786-2022).
***Number of months determined by the following criteria: Episodes must have at least 6 months below "-1" value of SPI Index. The count of months will start and finish with the values below "-0.75".**
****The month with the lowest value of each episode corresponds to the SPI index.**

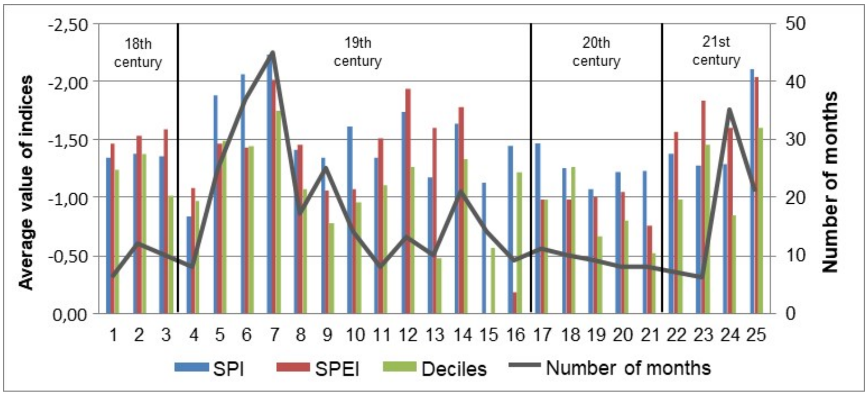

Figure 16: Representation of the mean values of the indices and the duration in months of the drought episodes described in Table 7.

4. DISCUSSION

The comparison between the results obtained from the historical data and the instrumental series is part of the main objective of this study. This comparison makes it possible to contrast the reliability of the methods used and to assess the consistency of the results obtained.

The combination of different *proxy* data expands the knowledge on the extreme hydrometeorological events, whether they be excesses or deficits, occurring in the past. In this case, the historical data and the instrumental series of Barcelona have allowed us to analyse one of the driest known periods in the study area (Table 8). The comparison of the standardised values of the historical series with the instrumental indices enables us to observe the synchrony between the historical *proxy* and the instrumental data (Figure 17). The coincidence of the duration of the episodes from the historical data and instrumental series is noteworthy. The only episode for which the durations are different is that of 1807, attributable to the fact that it mainly affected and for longer the southern regions of the Iberian Peninsula. In terms of the severity of the episodes, the coincidence between the two sets of data is also noteworthy, with the episodes with most documented cases coinciding with those with a lower SPI index. The only episode that does not follow this pattern is that of 1812, in which the number of negative ERE cases is relatively low. But, on the other hand, according to the SPI, it is the episode with the third lowest mean of the DSM period. The use of aspects related to the social vulnerability to drought and extending the length of the data collection in different locations would help to resolve these specific uncertainties and constitute lines of research to be developed in the future.

Episod. Num.	Date according to historical data		Month Num.	Date according to instrumental data		Month Num.	Number of cases		SPI episode average
	Onset	Ending		Onset	Ending		ERE Pos.	ERE Neg.	
3	12/1797	12/1799	25	03/1798	11/1799	21	37	78	-0.93
4	01/1807	07/1808	19	09/1807	04/1808	8	17	55	-0.84
5	03/1812	04/1814	21	05/1812	04/1814	24	24	44	-1.93
6	12/1815	11/1818	37	11/1815	11/1818	37	20	175	-2.06
7	01/1822	01/1826	40	01/1822	10/1825	46	41	279	-2.19

Table 8: Characteristics of the five principal drought episodes of the DSM according to historical data and instrumental series.

Figure 17 shows the coincidence of the droughts according to the historical data (positive values) with the negative oscillations shown by the SPI and SPEI indices. The overlapping of this information highlights the importance of the droughts in the final part of the DSM, specifically between 1815 and 1825, although the instrumental data indicate that this period could have started in 1812. For this reason, it is desirable to analyse in more detail the three drought episodes in which there is a high degree of alignment between the instrumental data the historical proxy data:

- That of 1798 stands out as it forms part of the precipitation irregularities typical of the Maldà Oscillation (Barriendos & Llasat, 2003). This drought occurred between two phases of intense rainfall. It was unique, but a situation of drought episodes alternating with floods or torrential rain is typical in areas with a Mediterranean climate.
- The drought of 1817 was different as it was the most severe according to the SPI index and was the year during which the most drought cases were recorded in the whole of the DSM (120). Despite this strong impact, mainly corresponding to the first half of 1817, the episode was not as long as that of 1822-1825 and, for this reason, according to the SPEI index, it was less severe than this latter episode.
- That of 1822-1825 stands out for its duration of around 40 months according to the rogations and 46 months according to the instrumental series. This not only makes it the longest episode of the DSM but also of the whole of the precipitation series of Barcelona (Table 8). Moreover, this episode is the one with the highest severity, both in terms of the accumulation of drought cases (279) and in terms of the SPI average for the episode as a whole. It is also worth mentioning that according to the SPEI index, this episode is the most severe of the entire Barcelona precipitation series.

Based on the standardised data of the number of drought series for the DSM period, the correlation coefficient has been calculated with the values of the different drought indices, with which the precipitation series of Barcelona has been analysed (Table 9). We can observe that the values of the three indices generate correlations of over -0.5; where the Deciles index has the greatest correlation value, which is logically inverted (-0.65). The same is confirmed for the coefficients of determination that verify that between 35% and 42% of the variability is explained by the behaviour of the variables used (drought indices vs. number of drought cases).

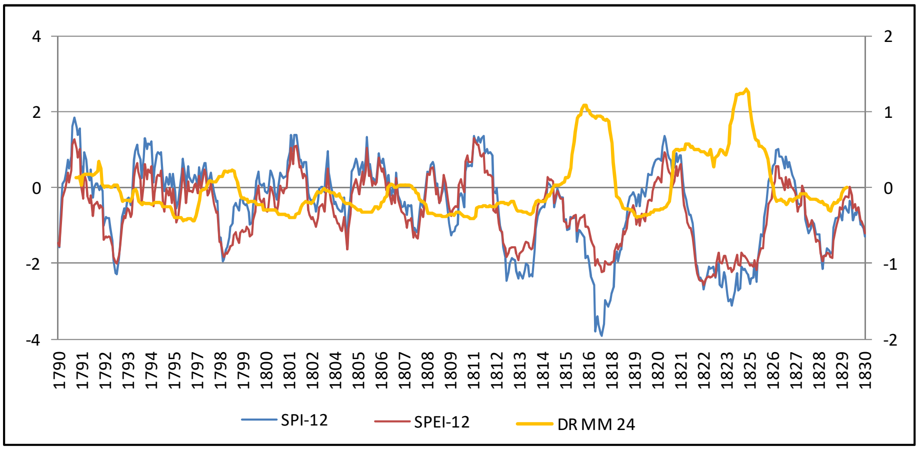

Figure 17: Comparison of the results of the drought indices (SPI and SPEI) and the two-year moving average of the standardised monthly values of the drought cases (DR).

Index	Correlation coefficient (R)	Correlation coefficient (R^2)
SPI	-0.62	0.38
SPEI	-0.59	0.35
Deciles	-0.65	0.42

Table 9: Correlation and determination coefficients

The study of extreme drought episodes in the past is important for understanding the behaviour of low frequency episodes and for addressing the droughts occurring in the context of climate change, which have erratic behaviour according to the most recent models (IPCC, 2021). Furthermore, the knowledge generated for the study over a long period of time also enables us to better understand the vulnerability of society in different historical contexts and the way in which it has adapted over time to respond to droughts.

Different studies carried out on droughts for the whole of the Mediterranean region for long time periods (Kim & Raible, 2021; Xoplaki, et al., 2018; Marcos-García, et al., 2017) reveal that it is one of the most vulnerable regions to drought within the context of global warming. Taking into account the results of this paper, it is considered that in order to underline the importance of droughts in the Mediterranean region, it is necessary to have the support of different drought indices, as well as other climatic indicators that help to determine their severity (Kim & Raible, 2021). The availability of older instrumental series is of great importance in order to find a wider range of drought severities and typologies than those found only by analysing the 20th century (Erfurt et al., 2020). This research combines historical instrumental data with dendrochronological records to analyse the period of the beginning of the nineteenth century in south-east Germany (Erfurt et al., 2020). With respect to the use of dendrochronological data to analyse the droughts and megadroughts of the past, the Old World Drought

Atlas is also worth mentioning (Cook et al., 2015). This publication includes a severe drought that occurred at the beginning of the nineteenth century, between the Little Ice Age and the Modern Climate period.

Other authors, particularly in the study of the Iberian Peninsula, have used historical data for classifying droughts in the period at the beginning of the nineteenth century (Domínguez-Castro et al., 2012; Gil-Guirado et al., 2019; Gil-Guirado & Pérez-Morales, 2019). It is worth highlighting the article by Domínguez-Castro et al., (2012), in which the historical data are combined with instrumental data to characterise the droughts of the period analysed in Spain. In this case, the same dry periods of great intensity are detected (1817 and 1824) by both the historical data and the instrumental series The authors conclude that the relationship between these droughts and external forcing factors is clear, but that more research is required to confirm this relationship.

Furthermore, the modelling used by (Kim & Raible, 2021) does not show any extraordinary occurrence of droughts for the Mediterranean region as a whole during the DSM period. Neither do these authors relate precipitation behaviour with that of those volcanic eruptions emitting more particles into the lower stratosphere, such as Tambora. According to their study, droughts occurring in the Mediterranean are due mainly to the internal dynamics of the climate system and not to external forcing factors (inter-tropical volcanic eruptions and solar radiation variations) (Kim & Raible, 2021). The same conclusion has been obtained for the Eastern Mediterranean region, although for another period than the one studied in this research (Xoplaki, et al., 2018). For these reasons, the conclusion may be drawn that the relationship between the external forcing factors can lead to different precipitation behaviour depending on the region in which specific conditions prevail.

For the case of the Iberian Peninsula, the combination of inter-tropical volcanic eruptions with positive phases of the North Atlantic Oscillation during the first two years after the eruption can result in dry periods for the Iberian Peninsula and in wet phases for Central Europe (Domínguez-Castro et al., 2012). In this respect, the lack of droughts detected in south-east Germany during the DSM period could reinforce this hypothesis (Erfurt et al., 2020). In this study of droughts for south-east Germany, despite the lack of droughts in the DSM period, there were temporal coincidences with other severe drought episodes, such as those occurring at the end of the nineteenth century (between the years 1857 and 1870) and at the beginning of the twenty-first century (2003 to 2018) (Erfurt et al., 2020). This period coincides with two of the most severe episodes of the twenty-first century according to the records of the instrumental precipitation series of Barcelona: the drought of 2007-2008 and that of 2015-2018, as we can see in Table 7.

5. CONCLUSIONS

The results obtained with this broad time-scale research contribute to a better understanding of drought episodes occurring in the early 21st century in the study area. Data collection and extension of databases according to objective 1, allows a substantial improvement of knowledge about drought patterns. It makes possible to work over a wider time period by detecting low frequency episodes, not always recorded in instrumental period. However, it also recognises the vast amount of information still unexplored in documentary sources.

The analysis of the megadrought occurred in the Spanish Mediterranean Basin during the period of the Late Dalton Minimum (1810-1830) allows to achieve objective 2 by comparing hydrometeorological episodes of excess (torrential rainfall) and deficit (droughts). By using documentary sources, it becomes clear that during the DSM exists an alternation between rainy and the dry periods. In contrast, during the previous climatic episode of the Malda oscillation (1760-1800), the behaviour of the precipitations was directly opposed to that of the DSM.

According to objective 3, one of the main results achieved in this research is the high negative correlation between the drought historical data and the instrumental precipitation series of Barcelona. This correlation validates the historical information for the study of climate droughts in historical perspective. Despite their different origins and methodologies, these two data sources have shown that they can provide information that is comparable, enabling the reinforcement of the importance of the episode recorded, either floods or droughts.

Regarding objective 4, the analysis of instrumental data shows the similar behaviour of severe droughts between the end of the LIA and the current context of Global Warming. On the other hand, the twentieth century does not show such a pattern of severe droughts.

The combination of historical documentary sources and instrumental sources in the detection of severe droughts offers positive results. The methodology for using documentary sources could be applied for periods or locations where instrumental series are not yet available.

In the light of the good results obtained from the combination of these two sources of climatic information, a future line of research for the Dalton Solar Minimum and other relevant climatic periods would consist of combining the historical data with data from other climatic proxies (especially dendrochronology) and instrumental pressure series, which would allow the understanding of the atmospheric processes on a synoptic scale that directly explain the most severe episodes of drought.

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AUTHOR CONTRIBUTION

Josep Barriendos: Data processing and analysis. Interpretation of the results. Preparation of graphic and cartographic material.

María Hernández Hernández: General revision of the texts and advice on the preparation of the materials.

Salvador Gil-Guirado: Methodological approach and advice on the conceptual criteria for defining drought.

Jorge Olcina Cantos: General review and advice on the conceptual criteria for defining drought.

Mariano Barriendos: Elaboration and organisation of information from historical sources.

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