Dear Editor, this is the point by point response to the reviewer's comments.

Reviewer.
I think that the authors have addressed some of the questions raised in my previous review and I recognize this effort. However, I think that some of my concerns have not been properly addressed.
- Physical meaning of the clusters. I think that the authors fail in providing a convincing explanation for their proposed clusters. In their reply they acknowledge that the differences between Lleida and Cervera are not due to climatic factors, but rather to the higher resilience of Lleida to precipitation shortage due to the irrigation system. Thus, rogations in Lleida should only detect the most extreme events and their sensitivity to drought is different. However this different sensibility to water shortage is not taken into account in the clustering, when all the series are treated equally.

We appreciate your previous comments that helped enhancing the quality of the manuscript. In the new version of the manuscript we have further addressed and re-organized the discussion to show the potential pitfalls of the cluster analysis and the use of rogation ceremonies as a climatic proxy. Please see new section from lines 393 to 512.
We have now included a new paragraph explaining the drawbacks when dealing with historical documents and clusters (now 437-484). We clarify your line "differences between Lleida and Cervera are not only due to climatic factors'. Rather we say 'the clusters might not only be collecting climatic information but also diverse agricultural practices or even species', which is considerably different.
All proxy records used to infer past climate conditions contain non-climatic information. For example, in tree-rings records, which are extensively used to develop reconstructions, climate explains between 40 to 60% of the tree-ring growth variance (in the best cases). This does not invalidate the proxy as a paleoclimatic source, but it adds a range of uncertainties and feasible hypothesis to elucidate that remaining unexplained percentage of variance. Here, the fact that Lleida is not included in the Mediterranean cluster, is precisely reflecting not only slightly different climatic conditions, but also a distinctive response of its population to drought events. As you point out in your comment, it might be only showing the most extreme events due to a higher resilience to droughts (because of their irrigation system), and that is why is indeed included in the Mountain cluster and not in the Mediterranean one. We hope that the new paragraphs included in the discussion would help addressing the different limitations of the use of rogation data as a climatic proxy.

A physically consistent explanation of the inclusion of the Teruel series in the Pyrenees cluster is not provided in the reply. According to figure 4, Teruel is only significantly correlated with Huesca, but the explained variance is lower that 4%. No other significant correlations are found for Teruel within this cluster.

In fact, we talk about a "Mountain cluster", which includes towns located within a higher elevation or latitude, such is the case of Teruel. This city is located at 915 m.a.s.l. being one of

the highest capitals in Europe. Although it is located south of the rest of the cities within the DIMOU cluster, its agreement with the general DIMOU (r=0.55, p<0.05) (as a basic quality control method) denotes that there is a coherent and common shared regional signal. All the DI local stations included in DIMOU show significant correlations with the regional DIMOU, suggesting that there are particular regional scale events. However, we agree that the climatic interpretation of the DIMOU cluster should be treated with caution.
We have now included these and other potential drawbacks in lines 437 to 484.

Consequently, I still think that the clusters have no climatological support, which rests validity to the rest of the analysis.

We agree partially with this comment. Two of the three clusters analyzed here (DIEV and DIMOU) have a strong climatological support. The additional quality control approaches (calibration/ verification and relationship between series) are likely to be robust enough for their interpretation. In addition, such results can be of special interest since DIEV and DIMOU represent geographical areas where other climate proxies (like tree-rings) are scarce.
We agree with specific limitations of the *pro-pluviam* rogations ceremonies as a climatic (drought) proxy in the Mountain cluster and we tried to explicitly expose such limitations in the new discussion section.

Validation of the series. I acknowledge the effort in validating the series with the inclusion of the Barcelona instrumental series, which shows an overlapping period with the rogation series. However, I do not think that the authors have provided a fair comparison since they are comparing a local series (Barcelona), with a Regional average (DIMED). This has several problems which have been treated in model verification (see for instance Gilleland et al 2009 and references therein). Since the Barcelona rogation series is available, they should provide the comparison of the two local series during the overlapping period if they want to provide a convincing validation. So, according to these points, the clustering, which is the most original part of the paper, should be reconsidered to get a partition based on the climatic signal in a convincing way. On the other hand a fair validation should be provided.

We have now included DIBCARCELONA as requested to complete our analysis (see new Figure 5) and further discussed the calibration/ verification approach (see lines 485-512).

Minor point
Language is still an issue and should be checked carefully. For example line 193 of the new version: '461 years of continues data'

Done.

Rogation ceremonies: key to understand past drought variability in northeastern Spain since 1650

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ABSTRACT

In the northeast of the Iberian Peninsula, drought recurrence, intensity, persistence and spatial variability have been mainly studied by using instrumental data covering the past ca. 60 years. Fewer studies have reconstructed drought occurrence and variability for the preinstrumental period using documentary evidence and natural proxies. In this study, we compiled a unique dataset of rogation ceremonies, religious acts to ask god for rain, from 13 cities in the northeast of Spain and investigated the annual drought variability from 1650 to 1899 AD. We converted the qualitative information into three regionally different coherent areas (Mediterranean, Ebro Valley and Mountain) with semiquantitative, annually resolved (December to August) drought indices according to the type of religious act. Both the Barcelona and the regional Mediterranean Drought Indices were compared with the instrumental series of Barcelona for the overlapping period (1787-1899) and we discovered a highly significant and stable correlation with the Standard Precipitation Drought Index of May with a 4 months lag (r=-0.46 and r=-0.53; p<0.001, respectively), asserting the validity of the local and regional Drought Indices derived from the historical documents as drought proxies. We found common periods with prolonged droughts (during the mid and late 18th century) and extreme drought years (1775, 1798, 1753, 1691 and 1817) associated with more blocking situations. A superposed epoch analysis (SEA) was performed to test the regional hydroclimatic responses after major tropical volcanic eruptions. The SEA shows a significant decrease in drought events one year after the volcanic events, which might be explained by the decrease in evapotranspiration due to decreases in surface temperatures and, consequently, the higher water availability that increases soil moisture. In addition, we discovered a common and significant drought response two years after the Tambora volcanic eruption in the three regional drought indices. Documented information on rogations thus contains important independent information to reconstruct extreme drought events for specific seasons in areas and periods for which instrumental information and other proxies are scarce.

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1. Introduction

Water availability is one of the most critical factors for human activities, human wellbeing and the sustainability of natural ecosystems. Drought is an expression of a precipitation deficit, which is often longer than a season, a year or even a decade. Drought leads to water shortages associated with adverse impacts on natural systems and socioeconomic activities, such as reductions in streamflow, crop failures, forest decay or restrictions on urban and irrigation water supplies (Eslamian and Eslamian, 2017). Droughts represent a regular, recurrent process that occurs in almost all climate zones. In the Mediterranean region, the impacts of climate change on water resources are of significant concern (García-Ruíz et al., 2001). Spain is one of the European countries with a large risk of drought caused by high temporal and spatial variability in the distribution of the precipitation (Vicente-Serrano et al., 2014; Serrano-Notivoli et al., 2017). Several recent Iberian droughts and their impacts on society and the environment have been documented in the scientific literature (e.g., Dominguez Castro et al., 2012; Trigo et al. 2013; Vicente-Serrano et al. 2014; Russo et al. 2015; Turco et al. 2017). For instance, during the period from 1990 to 1995, almost 12 million people suffered from water scarcity, the loss in agricultural production was an estimated 1 billion Euro, hydroelectric production dropped by 14.5 % and 63% of southern Spain was affected by fires (Dominguez Castro et al., 2012). One of the most recent droughts in Spain lasted from 2004 to 2005 (García-Herrera et al., 2007) and was associated with major socioeconomic impacts (hydroelectricity and cereal production decreased to 40% and 60%, respectively, of the average value).

In other European regions, drought intensity and frequency has largely been studied as their socio-economic and environmental impacts are expected to increase with climate change (e.g. Spinoni et al., 2018; Hanel et al., 2018). Long-term studies using instrumental meteorological observations have helped understanding European drought patterns at various spatial and temporal scales (e.g. Spinoni et al., 2015; Stagge et al., 2017). In addition, natural proxy data have provided a multicentennial long-term perspective in Europe by developing high-resolution drought indices derived mostly from tree-ring records (e.g. Büntgen et al., 2011; Cook et al., 2015). Finally, documentary records utilized in historical climatology have complemented the understanding of droughts across Europe (e.g. Brázdil et al., 2005, 2010). These studies, covering the last few centuries are usually focused in specific periods of extreme droughts and their societal impacts (e.g. Diodato and Bellochi, 2011; Domínguez-Castro et al., 2012) and yet, studies that attempt to develop continues drought indices for the last centuries, inferred from documentary evidences, remain an exception (e.g. Brázdil et al., 2013, 2018).

In the Iberian Peninsula, natural archives including tree-ring chronologies, lake sediments and speleothems have been used to infer drought variability before the instrumental period (Esper et al., 2015; Tejedor et al., 2016, 2017c; Benito et al., 2003, 2008; Pauling et al. 2006; Brewer et al., 2008; Carro-Calvo et al., 2013, Abrantes et al., 2017, Andreu-Hayles et al., 2017). Nevertheless, most of the highly temporally resolved natural proxy-based reconstructions represent high-elevation conditions during specific periods of the year (mainly summer e.g, Tejedor et al., 2017c). Spain has a high amount of documentary-based data with a good degree of continuity and homogeneity for many areas, which allows the derivation of important paleo climate information at different timescales and for various territories. Garcia-Herrera et al. (2003) describe the main archives and discuss the techniques and strategies used to derive climate-relevant information from documentary records. Past drought and precipitation patterns have been inferred by exploring mainly rogation ceremonies and historical records from Catalonia (Martin-Vide and Barriendos 1995; Barriendos, 1997; Barriendos and Llasat, 2003; Trigo et al. 2009), Zaragoza (Vicente-Serrano and Cuadrat, 2007), Andalusia (Rodrigo et al., 1998; 2000), central Spain (Domínguez-Castro et al., 2008; 2012; 2014; 2016) and Portugal (Alcoforado et al. 2000). In northeastern Spain, the most important cities were located on the riversides of the Ebro Valley, which were surrounded by large cropland areas (Fig. 1). Bad wheat and barley harvests triggered socio-economic impacts, including the impoverishment or malnutrition of families, the severe alteration of the market economy, social and political conflicts, marginality, loss of population due to emigration and starvation and diseases and epidemics, such as those caused by pests (Tejedor, 2017a). Recent studies have related precipitation/drought variability in regions of Spain to wheat yield variability (Ray et al., 2015; Esper et al. 2017). The extent of impacts caused by droughts depends on the socio-environmental vulnerability of an area. This is related to the nature and magnitude of the drought and the social structure of societies, such as agricultural-based societies including trades (Scandyln et al., 2010; Esper et al. 2017). During the past few centuries, Spanish society has been strongly influenced by the Catholic Church. Parishioners firmly believe in the will of God and the church to provide them with better harvests. They asked God to stop or provoke rain through rogations, a process created by bishop Mamertus in AD 469 (Fierro, 1991). The key factor in evaluating rogation ceremonies for paleo climate research is determining the severity and duration of adverse climatic phenomena based on the type of liturgical act that was organized after the deliberation and decision-making of local city councils (Barriendos, 2005). Rogations are solemn petitions by believers to ask God specific requests (Barriendos 1996, 1997). *Pro-pluviam* rogations were conducted to ask for precipitation during a drought, and they therefore provide an indication of drought episodes and clearly identify climatic anomalies and the duration and severity of the event (Martín-Vide & Barriendos, 1995; Barriendos, 2005). In contrast, *pro-serenitate* rogations were requests for precipitation to end during periods of excessive or persistent precipitation, which caused crop failures and floods. In the Mediterranean basin, the loss of crops triggered important socio-economic consequences and was related to insufficient rainfall. Rogations were an institutional mechanism to address social stress in response to climatic anomalies or meteorological extremes (e.g. Barriendos, 2005). The municipal and ecclesiastical authorities involved in the rogation process guaranteed the reliability of the ceremony and maintained a continuous documentary record of all rogations. The duration and severity of natural phenomena that stressed society can be reflected by the different levels of liturgical ceremonies that were applied (e.g. Martin-Vide and Barriendos, 1995; Barriendos, 1997; 2005). Through

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these studies, we learned that the present heterogeneity of drought patterns in Spain also occurred in the past few centuries, in terms of the spatial differences, severity and duration of the events (Martin-Vide, 2001, Vicente-Serrano 2006b). However, a compilation of the main historical document datasets that have been compiled over the past several years is lacking, impeding the creation of a continuous record of drought recurrences and intensities in the northeast of the Iberian Peninsula.

Here we compiled 13 series of historical documentary information of the *pro-pluviam* rogation data from the Ebro Valley and the Mediterranean Coast of Catalonia (Fig. 1) from 1438 to 1945 (Tab. 1). Regarding the location of the cities, they cover a wide range spanning from Barcelona, which is near the sea (9 m a.s.l.), and Teruel (915 m a.s.l.) (Fig 1). Although some periods have already been analyzed for certain cities (i.e., Zaragoza in 1600-1900 AD by Vicente-Serrano and Cuadrat, 2007; Zaragoza, Calahorra, Teruel, Vic, Cervera Girona, Barcelona, Tarragona and Tortosa in 1750-1850 AD by Dominguez-Castro et al., 2012; La Seu d'Urgell, Girona, Barcelona, Tarragona, Tortosa and Cervera in 1760-1800 AD by Barriendos and Llasat, 2003), this is the first systematic approach analyzing all existing information for northeastern Spain, including new unpublished data for Huesca (1557-1860 AD) and Barbastro (1646-1925 AD) and examining the 13 sites jointly for a period of 250 years (1650-1899 AD). We analyzed droughts across the sites and identify extreme drought years and common periods in frequency and intensity. We also analyze statistical links between drought indices and major tropical volcanic events in order to determine the effects of strong eruptions on regional droughts.

2. Methods

2.1. Study area

The study area comprises the northeastern part of Spain, with an area of approximately 100,000 km^2, and includes three geological units, the Pyrenees in the north, the Iberian Range in the south, and the large depression of the Ebro Valley that separates them (Fig. 1). The Ebro Valley has an average altitude of 200 m a.s.l. The Ebro Valley climate can be characterized as a Mediterranean type climate, with warm summers, cold winters and increasing continental characteristics with distance from the coast. Some geographic aspects determine its climatic characteristics; for example, several mountainous chains isolate the valley from moist winds, preventing precipitation. Thus, in the central areas of the valley, annual precipitation is low, with small monthly variations and an annual precipitation in the central Ebro Valley of approximately 322 mm (AEMET, 2012). In both the Pyrenees and the Iberian Range, the main climatic characteristics are related to a transition from oceanic/continental to Mediterranean conditions in the East. In addition, a gradually higher aridity towards the east and the south is caused by the barrier effect of the most frequent humid air masses (Vicente-Serrano, 2005; López-Moreno & Vicente-Serrano, 2007). Areas above 2000 m a.s.l. receive approximately 2,000 mm of precipitation annually, increasing to 2,500 mm of precipitation in the highest peaks of the mountain range (García-Ruiz, et al., 2001).

The annual precipitation in the Mediterranean coast is higher than that in the middle Ebro Valley and ranges from approximately 500 mm in Tortosa to 720 mm in Girona (Serrano-Notivoli et al., 2017).

2.2. From historical documents to climate: Development of drought index for each location in NE Spain from 1650 to 1899 AD

Historical documents from 13 cities in the northeast of Spain were compiled into a novel dataset by using a consistent approach (Fig. 1, Tab. 1, Tab. S1). These historical documents are the rogation ceremonies reported in the 'Actas Capitulares' of the municipal archives or main cathedrals. The extension of the consulted documents (described in Table S1) ranges from 461 years of continuous data in Girona, to 120 years in Lleida, with an average of 311 years of data on each station. Rogations not only were religious acts but also were supported by the participation of several institutions; agricultural organizations and municipal and ecclesiastical authorities analyzed the situation and deliberated before deciding to hold a rogation ceremony (Vicente-Serrano and Cuadrat, 2007). Usually, the agricultural organizations would request rogations when they observed a decrease in rainfall, which could result in weak crop development. Then, municipal authorities would recognize the setback and discuss the advisability of holding a rogation ceremony. Whether a rogation was celebrated or not was not arbitrary, since rogations had a price paid by public coffers. When the municipal authorities decided to hold a rogation, the order was communicated to the religious authorities, who placed the rogation on the calendar of religious celebrations and organized and announced the rogation. Previous studies have reported that winter precipitation is key for the final crop production in dry-farming areas of the Ebro Valley (wheat and barley; Austin et al., 1998a, 1998b; McAneney and Arrué, 1993; Vicente-Serrano and Cuadrat, 2007). In addition to winter rogations, most of the rogations were held during the vegetation growth period (March-May) and harvest period (June-August), since the socio-economic consequences when the harvest was poor were more evident during these periods. Thus, it is reasonable to consider those rogations in an index from December to August.

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The qualitative information contained in the rogations was transformed into a semiquantitative continuous monthly series following the methodology of the Millennium Project (European Commission, IP 017008-Domínguez-Castro et al., 2012). Only *pro-pluviam* rogations were included in this study. According to the intensity of the religious act, which were homogenously performed throughout the Catholic territories and triggered by droughts, we categorized the events in 4 levels from low to high intensity: 0, there is no evidence of any kind of ceremony; 1, a simple petition within the church was held; 2, intercessors were exposed within the church; and 3, a procession or pilgrimage took place in the public itineraries, the most extreme type of rogation (see Tab. 2). Although rogations have appeared in historical documents since the late 15th century and were reported up to the mid 20th century, we restricted the common period to 1650-1899 AD, since there are a substantial number of data gaps before and after this period, although some stations do not extent the full period. A continuous drought index

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(DI) was developed for each site by grouping the rogations at various levels. A simple approach, similar to that of Martín-Vide and Barriendos (1995) and Vicente-Serrano and Cuadrat (2007), was performed. The annual DI values were obtained by determining the weighted average of the number of level 1, 2 and 3 rogations recorded between December and August in each city. The weights of levels 1, 2 and 3 were 1, 2, and 3, respectively. Accordingly, the drought index for each city is a continuous semiquantitative value from 0, indicating the absence of drought, to a maximum of 3 (Figure 2A).

2.3. Clustering station drought to regional drought indices from 1650 to 1899 AD

To develop regional drought indices, we performed a cluster analysis (CA) that separates data into groups (clusters) with minimum variability within each cluster and maximum variability between clusters. We selected the period of common data 1650-1770 to perform the cluster analysis. The main benefit of performing a cluster analysis (CA) is that it allows similar data to be grouped together, which helps in the identification of common patterns between data elements. To assess the uncertainty in hierarchical cluster analysis, the R package 'pvclust' (Suzuki and Shimodaira, 2006) was used. We used the Ward's method in which the proximity between two clusters is the magnitude by which the summed squared in their joint cluster will be greater than the combined summed square in these two clusters SS12−(SS1+SS2) (Ward, 1963; Everitt et al., 2001). Then, the root of the square difference between co-ordinates of pair of objects is computed with its Euclidian distance. Finally, for each cluster within the hierarchical clustering, quantities called p-values are calculated via multiscale bootstrap resampling (1000 times). Bootstrapping techniques does not require assumptions such as normality in original data (Efron, 1979) and thus represents a suitable approach applied to the semiquantitative characteristics of drought indices (DI) derived from historical documents. The *p-value* of a cluster is a value between 0 and 1, which indicates how strongly the cluster is supported by the data. The package 'pvclust' provides two types of *p-values*: AU (approximately unbiased *p-value*) and BP (bootstrap probability) *value*. AU *p-value* is computed by multiscale bootstrap resampling and is a better approximation of an unbiased *p-value* than the BP value computed by normal bootstrap resampling. The frequency of the sites falling into their original cluster is counted at different scales, and then the *p-values* are obtained by analyzing the frequency trends. Clusters with high AU values, such as those >0.95, are strongly supported by the data (Suzuki and Shimodaira, 2006). Therefore, in this study, sites belonging to the same group were merged by means of an arithmetical average (Eq.1).

Eq.1 $Regional\ Drought\ Index\ (x) = (x_1 + x_2 + x_3 \ldots)/\mathrm{n}$

where x_n represents each individual annual drought index, and n is the number of drought indices per cluster. Then, to evaluate the relationship of each site's rogations, we performed a matrix correlation (Spearman) between the new groups derived from the cluster and each individual drought index for the period of 1650-1899.

2.4. Validation of the regional Drought indices against overlapping instrumental series.

To better understand the relationship between the derive drought indices and the instrumental series, we used the longest instrumental precipitation and temperature series covering the period 1786-2014 AD (Prohom et al., 2012; Prohom et al., 2015) for the city of Barcelona and thus overlapping the rogation ceremony's period of the local DI of Barcelona (DIBARCELONA) from 1786 to 1899 AD. However, the instrumental series was homogenized and completed including data from cities nearby and along the Mediterranean coast (see Prohom et al., 2015 for details). Therefore, the instrumental series is containing coherent regional information from a Mediterranean section similar to our regional DIMED. We then calculated the Standardized Precipitation Index (SPI, McKee et a., 1993) and the Standardized Evapotranspiration and Precipitation Index (SPEI, Begueria et al., 2014) and calculated Spearman correlation between DIMED and the SPI/SPEI at different time scales including a maximum lag of 12 months covering the period 1787-1899. To further explore the relationship between the drought indices inferred from historical documents and the instrumental drought indices through time, we performed 30- and 50-years moving correlations.

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2.5. Detecting extreme drought years and periods in the northeast of Spain between 1650-1899 AD and links to large-scale volcanic forcing

To identify the extreme drought years, we selected those years above the 99th percentile of each regional drought index and mapped them in order to find common spatial patterns. In addition, the 11-year running mean performed for each drought index helped highlight drought periods within and among the drought indices. Finally, since rogation ceremonies are a response of the population to an extreme event, we performed a superposed epoch analysis (SEA; Panofsky and Brier, 1958) of the three years before and after the volcanic event, using the package 'dplR' (Bunn, 2008) to identify possible effects on the hydroclimatic cycle caused by volcanic eruptions. The largest (Sigl et al., 2015) volcanic eruptive episodes chosen for the analysis were 1815, 1783, 1809, 1695, 1836, 1832, 1884 and 1862. In addition, we performed the SEA only with the largest eruption of this period, the Tambora eruption in the year 1815.

3. Results

3.1. From historical documents to climate: Development of drought index for each location in NE Spain from 1650 to 1899 AD

Performing a weighted average of the monthly data (see methods), we converted the ordinal data into continuous semiquantitative index data. As a result, we developed an annual drought index (from the previous December to the current August) for each of the 13 locations that contains continuous values from 0 to 3 collected from information on the annual mean extreme droughts of each year. The EDCF (Fig.2A) confirmed that the new drought indices can be treated as a continuous variable since the Drought Index can take almost infinite values in the range from 0 to 3. Then, to study drought across the region, we performed a cluster analysis including the annual drought indices of the 13 cities. These data were then used to study the hydrological responses after strong tropical eruptions.

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3.2. Clustering station drought to regional drought indices from 1650 to 1899 AD

The cluster analysis (CA, see methods) using the DI of the 13 locations for the period of 1650-1899 AD revealed three significantly coherent areas, hereafter known as Mountain, Mediterranean and Ebro Valley (Fig. 3). The first cluster includes cities that are similar in altitude (Teruel, La Seu) and similar in latitude (Barbastro, Lleida, Huesca, Girona, see Fig. 1). The cities within the second and third clusters are near the Ebro River (Calahorra, Zaragoza and Tortosa) or have similar climatic conditions (Cervera, Vic, Barcelona, Tarragona). Clusters two and three suggest (Fig. 3) that the coherence of the grouping can be explained by the influence and proximity of the Mediterranean Sea (Tortosa, Cervera, Tarragona, Vic and Barcelona) and the influence of a more continental climate (Zaragoza and Calahorra). Accordingly, three regional drought indices were developed by combining the individual DIs of each group; DI Mountain (DIMOU), composed of Barbastro, Teruel, Lleida, La Seu, and Girona; DI Mediterranean (DIMED), composed of Tortosa, Cervera, Tarragona, Vic and Barcelona, and DI Ebro Valley (DIEV), composed of Zaragoza and Calahorra. Resulting drought indices in regional DI series can also varies from 0 to 3 but showing a quite continuous distribution range (Figure 2B).

The Spearman correlation matrix for the period of 1650-1899 AD confirms the high and significant ($p<0.05$) correlations between each individual DI and its corresponding group, asserting the validity of the new DI groups (Fig. 4). The correlations among the cluster drought indices range from 0.76 (between DIEV and DIMED) to r=0.38 (between DIEV and DIMOU) and r=0.42 (between DIMED and DIMOU). In DIEV, both of the local DIs show similar correlations (Zaragoza, r=0.73; Calahorra, r=0.75). In the DIMED cluster, the high correlations among the members show a strong coherency. DIMOU is the most heterogeneous cluster, with correlations of r=0.57 for Barbastro and r=0.33 for La Seu. Although each individual DI within this group and within the DIMOU shows significant correlation, when individual DIs are compared between each other, some correlation values are not significant ($p<0.05$).

3.3. Validation of the regional Drought indices against overlapping instrumental series.

The maximum Spearman correlation (r=-0.46; p<0.001) between the Barcelona Drought Index and the instrumental SPI over the full 113-year period (1787-1899 AD; Fig.5C) is found for the SPI of May with a lag of 4 months (SPI_{MAY_4} hereafter). Slightly lower, though still significant correlation is obtained when using the SPEI of May with a lag of 4 months ($SPEI_{MAY\_4}$) (r=-0.41; p<0.001, Fig.5D). The regional Mediterranean

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Drought Index shows moderately higher correlations with the instrumental SPI (r=-0.53; p<0.001) and SPEI (r=-0.50; p<0.001) computed for the same period and time scale. The moving correlations between DIMED and SPI_{MAY_4} for 30 and 50 years (Fig.5A; Fig.5B) present higher and more stable correlations through the full period than with the DIBARCELONA. The relationship with the $SPEI_{MAY\_4}$ is also high and stable throughout the overlapping period, although lower than with SPI_{MAY_4}. The next step (iv) will address the selection of extreme drought years and periods within the 250 years from 1650-1899 AD using information from the cluster analysis.

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3.4. Detecting extreme drought years and periods in the northeast of Spain between 1650-1899 AD and links to large-scale volcanic forcing

According to the cluster grouping, the three new spatially averaged drought indices (DIEV, DIMED and DIMOU) are presented in Fig. 6. Mountain DI (DIMOU) had the least number of drought events and a maximum DI of 1.6 in 1650 AD. The Ebro Valley DI (DIEV) had the highest number of droughts (inferred by the highest number of positive index values) followed by the third region (Mediterranean DI, DIMED). The 17th and 18th centuries exhibited a relatively high number of strong droughts (Fig. 6). A drought period, as indicated by the high positive index values over the duration of the DIs in all three series, occurred from 1740 to 1755 AD. The lowest DIs were found at the end of the 19th century; thus, this period experienced a reduced drought frequency. The 11-year running mean shows common periods with low DI values, such as 1706-1717, 1800-1811, 1835-1846 and 1881-1892, which we infer to be 'normal' or without droughts. On the other hand, 1678-1689, 1745-1756, 1770-1781, and 1814-1825 are periods with continuously high DIs, indicating that significant droughts affected the crops during these periods and intense rogation performances were needed.

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In the Ebro Valley, the most extreme years (Fig. 6) (according to the 99% percentile of the years 1650-1899) were 1775 (drought index value of 2.8), 1798 (2.7), 1691 (2.6), 1753 (2.5) and 1817 (2.5). Most of these extreme drought years can also be found in DIMED 1753 (2.6), 1775 (2.5), 1737 (2.3), 1798 (2.2) and 1817 (2.2). In DIMOU, the extreme drought years occurred in the 17th century: 1650 (1.6), 1680 (1.5), 1701 (1.5) and 1685 (1.4). These extreme drought years are spatially displayed in Fig. 7. In the years 1775 and 1798, the Ebro Valley, Mediterranean and some mountain cites suffered from severe droughts. It is notable that the year 1650 in the Mountain area presented high values of DI, while the other locations had very low DI values (DIEV=0.4; DIMED=0.8).

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We performed a superposed epoch analysis (SEA, see methods) to study the drought response over NE Iberia to major volcanic eruptions (Fig. 8a). The figure shows significant decreases (ρ<0.05) in the Ebro Valley and Mediterranean DI values during the year of and one year after volcanic events. We did not find a post-volcanic drought response in the Mountain area. No significant response was found for any of the DIs two or three years after the volcanic eruptions, including the major volcanic eruptions. However, two years after the Tambora eruption in April 1815, there was a significant

($\rho<0.05$) increase in the three drought indices (DIEV, DIMED and DIMOU) (Fig. 8b), in agreement with findings of Trigo et al. (2009).

4. Discussion

The exploration of historical documents from the main Cathedrals or the municipal city archives, the so called 'Actas Capitulares', yielded the different types and payments of the rogation ceremonies that were performed in drought stress situations. In fact, it is challenging to determine whether the decrease in the number of rogations at the beginning and at the end of the 19th century is due to the lack of droughts, the loss of documents, or a loss of religiosity within these periods. For instance, after the Napoleonic invasion (1808-1814) and the arrival of new liberal ideologies (Liberal Triennial 1820-1823), there was a change in the mentality of people in the big cities. These new liberal ideas were concentrated in the places where commerce and industry began to replace agriculturally based economies, leading to strikes and social demonstrations demanding better labor rights. New societies were less dependent on agriculture; hence, in dry spells, the fear of losing crops was less evident and fewer rogations were performed. In summary, the apparent low frequency of rogations in the 19th century could be explained by a combination of political instability and the loss of religiosity and historical documents.

Further limitations when dealing with historical documents as a climatic proxy are related to the need of converting binomial qualitative information (occurrence or not of rogation ceremonies) into quantitative data (e.g. Vicente-Serrano and Cuadrat, 2007; Dominguez-Castro et al., 2008). Here, we follow the methodology proposed in the Millennium Project (European Commission, IP 017008) and applied also in Domínguez-Castro et al., (2012). According to such proceedings and considering both the occurrence or not of rogation ceremonies and the intensity of the religious acts, the information contained in historical documents can be transformed into semiquantitative time series (including continuous values from 0 to 3). To that extent, the ECDF analysis helped understanding the nature of the historical documents when transformed into semiquantitative data, confirming that they can be treated as a continuous variable. Then, by aggregating such annual values we developed a continuous semiquantitative drought index (DI) where values can range from cero (absence of drought) to a maximum of 3 (severe drought). This set of procedures technically solves the structural problem of the data. However, we are adding complexity to its interpretation since, for example, an index of level 2 does not necessarily imply that a drought was twice as intense as a drought classified as level 1, nor that the change in the intensity of droughts from level 1 to level 2 or from level 2 to 3 has to be necessarily equivalent. Hence the interpretation of these indices must be made taking into account these considerations.

Besides, to further calibrate the potential of this source of information as a climatic proxy, we need to consider the existence of coherent spatial patterns in the distribution of droughts. The instrumental climate data is subject to quality controls to determine

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the extent to which that patterns are reflecting elements of the climatic cycle or may be due to errors of measurement, transcription of information etc (e.g. Alexandersoon, 1986). Here, to conduct such process, the local series are compared with the regional reference series as a basic element of quality control (e.g. Serrano-Notivoli et al., 2017). The interpretation of other proxies, such as tree-ring records are subject to similar quality control procedures to guarantee the spatial representativeness of the information they contain (e.g. Esper et al., 2015; Tejedor et al., 2017c).

The use of similar methods for quality control or analysis of spatial representativeness of the rogation series encompass specific pitfalls such as; i) instrumental weather series can be compared with nearby series (including networks of thousands of weather stations) (e.g. Serrano-Notivoli et al., 2017) whereas that proximity does not occur so intensively in the rogation series ii) Other proxy records such as tree-ring chronologies are developed from information obtained from tens or hundreds of trees to ensure the representativeness of the resulting series (Duchesne et al., 2017). At the same time, these resulting chronologies share an observational period with the climatic data allowing the calibration/ verification approach (Fritts et al., 1990).

In general, however, none of these quality control options are viable in the rogation series since i) the local series are separated by tens or hundreds of kilometers, ii) They do not overlap in time with observational weather series, which hinders a rigorous calibration-verification approach, iii) the structure of the data itself (binomial or semiquantitative at best) does not facilitate the calibration/ verification approach in the few cases in which this control is feasible.

In this work, being aware of these drawbacks, we deal with the problem of analyzing the spatial representativeness of the rogation series through a cluster analysis. We thus identify the extent to which the local rogation series show similar patterns to those observed in neighboring records and can therefore be considered as representative of the climate behavior at a sub-regional scale. Clustering is a descriptive technique (Soni, 2012), the solution is not unique, and the results strongly rely upon the analyst's choice of parameter. Yet, we found three significant (p<0.05) and consistent structures across the drought indices based on historical documents. DIEV shows a robust and coherent cluster associated with droughts in the Ebro Valley area, including the cities of Zaragoza and Calahorra. The high correlation among the local Drought Indices suggests an underlying coherent climatic signal. DIMED shows also a robust and coherent cluster associated with droughts in the Mediterranean coast area, including high correlation between the local Drought Indices of Tortosa, Tarragona, Barcelona, Vic and Cervera. The high correlation between DIEV and DIMED is suggesting similar climatic characteristics. Besides, the main cities among these two clusters are sharing similar agrarian and political structures, supporting the comparison. Finally, we found that DIMON shows a less robust and complex structure. This cluster includes local Drought Indices located in mountain or near mountain environments. Although there is a high correlation between the local DIs and the regional DIMOU suggesting a common climatic signal, the low correlation among local Drought Indices might be explained by the fact

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We can conclude that DIMOU has a weaker climatological support and thus it should be interpreted with particular caution. However, this important constraint in the interpretation of DIMOU is not so problematic from a practical point of view since it represents an area in which there are other proxy records (e.g. tree-rings) covering a wide spatio-temporal scale including proved valuable skills as drought proxies (e.g. Tejedor et al., 2016; 2017c). On the contrary, the consistency of the clusters observed in the Ebro Valley and the coastal zones (DIMED and DIEV) is especially encouraging and reflects a high potential of rogations as a drought proxy. It is precisely in these areas where there are no relict forests due to human intervention and therefore no centennial tree-ring reconstructions for inferring past climates can be developed. Consequently, in these environments, the information from historical documents may be especially relevant.

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The confirmation of the rogation ceremonies as a valid drought proxy (even if only in some environments) requires an additional procedure; the calibration/verification approach. However, the reliable and continuous rogation documents end at the 19th century, whereas the instrumental weather data begins generally in the 20th century (Gonzalez-Hidalgo et al., 2011). In the study area, only the continuous and homogenized instrumental temperature and precipitation series of Barcelona (Prohom et al., 2012; 2015) overlap the existing Drought Indices. Our results suggest that rogation ceremonies are not only valid as local indicators (good calibration/ verification with the local DIBARCELONA), but they also have regional representativeness (DIMED) and provide valuable climatic information (good calibration/ verification with the regional DIMED). To the best of our knowledge this is the first time that rogation ceremonies in the Iberian Peninsula are calibrated with such a long instrumental period. The correlation is maximized in May, the key month for the development of the harvest. In addition, the accumulated of 4 months is confirming the importance of the end of winter and spring

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These findings open a new line of research that the authors will continue exploring in future studies. We believe that these results highlight the validity of the Drought Indices to be consider as continuous variables. In addition, by performing this analysis we also confirm that the grouping made by the cluster analysis demonstrates spatial coherency among the historical documents. For some places, such as the mountain areas, where the population had other ways of life in addition to agriculture, *pro-pluviam* rogation ceremonies may have a weaker climatic significant. However, *pro-pluviam* rogations may be especially relevant in valleys and coastal areas where there are no other climatic proxies.

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Compared to other drought studies based on documentary sources, the persistent drought phase affecting the Mediterranean and the Ebro Valley areas in the second half of the 18th century is similar to that found in Vicente-Serrano and Cuadrat, (2007) for Zaragoza. The results for the second half of the 18th century also agree with the drought patterns previously described for Catalonia (Barriendos, 1997, 1998; Martín-Vide and Barriendos, 1995). Common drought periods were also found in 1650-1775 for Andalusia (Rodrigo et al., 1999, 2000) and in 1725-1800 for Zamora (Domínguez-Castro et al., 2008). In general, based on documentary sources from Mediterranean countries, the second half of the 18th century has the highest drought persistency and intensity, which may be because there were more blocking situations in this period (Luterbacher et al. 2002, Vicente-Serrano and Cuadrat, 2007). The period of 1740-1800 AD coincides with the so-called 'Maldá anomaly period'; a phase characterized by strong climatic variability, including extreme drought and wet years (Barriendos and Llasat, 2003). The 18th century is the most coherent period, including a succession of dry periods (1740-1755), extreme years (1753, 1775 and 1798) and years with very low DIs, which we interpret as normal years. Next, the period from 1814-1825 is noteworthy due to its prolonged drought. The causes of this extreme phase are still unknown. However, Prohom et al. (2016) suggested these years experienced a persistent situation of atmospheric blocking and high-pressure conditions.

In the Ebro Valley and the Mediterranean area, rogation ceremonies were significantly less frequent in the year of and one year after volcanic eruptions. Such patterns may be explained by the volcanic winter conditions, which are associated with reductions in temperature over the Iberian Peninsula 1-3 years after the eruption (Fischer et al., 2007; Raible et al., 2016). The lower temperature is experienced in spring and summer after volcanic eruptions compared to spring and summer conditions of nonvolcanic years. This might be related to a reduction in evapotranspiration, which reduces the risk of droughts. This reinforces the significance of volcanic events in large-scale climate changes. In addition, the lower temperatures may benefit the soil moisture of croplands.

Furthermore, a significant increase in the intensity of the droughts was observed two years after the eruptive Tambora event in the third cluster (Mountain, Fig. 3). The normal conditions in the year of and the year after the Tambora eruption and the increased drought intensity two years after the event are in agreement with recent findings about hydroclimatic responses after volcanic eruptions (Fischer et al., 2007; Wegmann et al., 2014; Rao et al., 2017; Gao and Gao 2017) though based on tree ring data only. In addition, Gao and Gao, (2017) highlight the fact that high latitude eruptions tend to cause drier conditions in western-central Europe two years after the eruptions. Rao et al., (2017) suggested that the forced hydroclimatic response was linked to a negative phase of the East Atlantic Pattern (EAP), which causes anomalous spring uplift over the western Mediterranean. This pattern was also found in our drought index for the Tambora eruption (1815 AD), but no significant pattern was found in the NE of Spain for the other major (according to Sigl et al., 2015) volcanic eruptions. In particular, the mountain areas show less vulnerability to drought compared to the other regions. This is mainly due to the fact, that mountainous regions experience less evapotranspiration, more snow accumulation and convective conditions that lead to a higher frequency of thunderstorms during the summertime.

Conclusions

We developed a new dataset of historical documents by compiling historical records (rogation ceremonies) from 13 cities in the northeast of the Iberian Peninsula. These records were transformed into semiquantitative continuous data to develop drought indices (DIs). We regionalized them by creating three DIs (Ebro Valle, Mediterranean and Mountain), which cover the period from 1650 to 1899 AD. The intensity of the DI is given by the strength and magnitude of the rogation ceremony, and the spatial extent of the DI is given by the cities where the rogations were held.

Our study highlights three considerations: i) the spatial and temporal resolution of rogations should be taken into account, particularly when studying specific years, since the use of *pro-pluviam* rogations gives information about drought periods and not about rainfall in general. Accordingly, it must be stressed that the drought indices developed here are not precipitation reconstructions; rather, they are high-resolution extreme event reconstructions of droughts spells. The comparison of these results with other continuous proxy records must be carried out with caution (Dominguez-Castro et al., 2008), although here we found a very high and stable correlation with the instrumental series for the overlapping period, which opens new lines of research. ii) The validity of rogation ceremonies as a high-resolution climatic proxy to understand past drought variability in the coastal and lowland regions of the northeastern Mediterranean Iberian Peninsula is clearly supported by our study. This is crucial, considering that most of the high-resolution climatic reconstruction for the northern Iberian Peninsula have been developed using tree-ring records collected from high-elevation sites (>1,600 m a.s.l.) in the Pyrenees (Büntgen et al., 2008, 2017; Dorado-

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Liñán et al., 2012) and the Iberian Range (Esper et al., 2015, Tejedor et al., 2016, 2017a, 2017b, 2017c), thus inferring the climate of mountainous areas. iii) Particularly in the Mediterranean and in the Ebro Valley areas, imprints of volcanic eruptions are significantly detected in the drought indices derived from the rogation ceremonies. These results suggest that DI is a good proxy to identify years with extreme climate conditions in the past at low elevation sites.

In addition, recent studies have emphasized the great precipitation (González-Hidalgo, et al., 2011; Serrano-Notivoli et al., 2017) and temperature variabilities (González-Hidalgo, et al., 2015) within reduced spaces, including those with a large altitudinal gradient, such as our study area. In addition, the rogations' historical data covers a gap within the instrumental measurement record of Spain (i.e., which starts in the 20th century). Hence, rogation data are key to understanding the full range of past climate characteristics (in lowlands and coastal areas) to accurately contextualize the current climate change. We encourage the use of further studies to better understand past droughts and their influence on societies and ecosystems; learning from the past can help adaptation in the future, especially because climate variability is predicted to increase in the same regions where climate variability historically explained most of the variability in crop yield.

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Author Contributions statement

E.T., and J.M.C. conceived the study. J.M.C. and M.B. provided the data. E.T. and M.d.L. conducted the data analysis, and E.T. wrote the paper with suggestions of all the authors. All authors discussed the results and implications and commented on the manuscript at all stages.

Competing interests statement

The authors declare no competing interests.

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Figures and tables

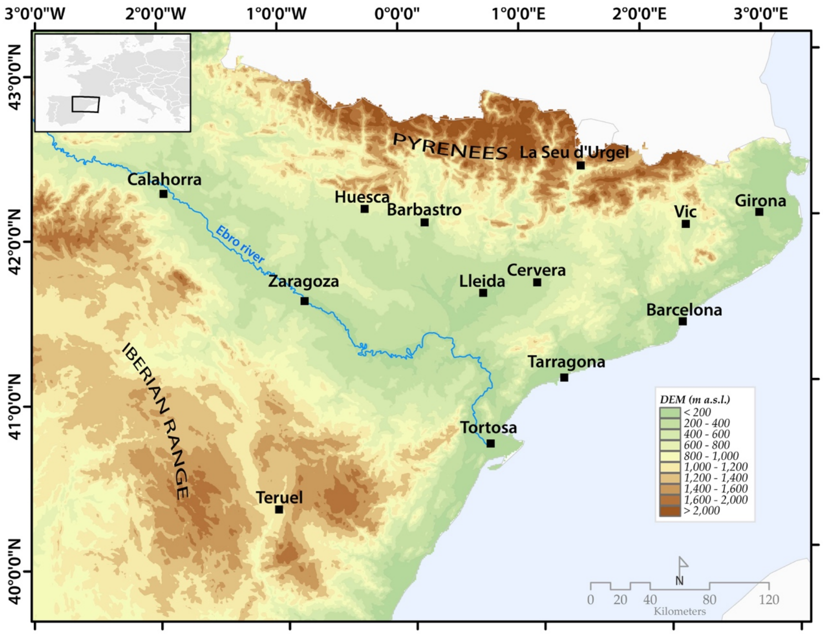

Figure 1. Location of the historical documents in the northeast of Spain.

Site	**Latitude (degrees)**	**Longitude (degrees)**	**Altitude (m.a.s.l.)**	**Start (Years AD)**	**End**	**Extension (years)**
Zaragoza	41.64	-0.89	220	1589	1945	356
Teruel	40.34	-1.1	915	1609	1925	316
Barbastro	42.03	0.12	328	1646	1925	279
Calahorra	42.3	-1.96	350	1624	1900	276
Huesca	42.13	-0.4	457	1557	1860	303
Girona	42.04	2.93	76	1438	1899	461
Barcelona	41.38	2.17	9	1521	1899	378
Tarragona	41.11	1.24	31	1650	1874	224
Tortosa	40.81	0.52	14	1565	1899	334
LaSeu	42.35	1.45	695	1539	1850	311
Vic	41.92	2.25	487	1570	1899	329
Cervera	41.67	1.27	548	1484	1850	366
Lleida	41.61	0.62	178	1650	1770	120

Table 1. Historical document characteristics in the northeast of Spain.

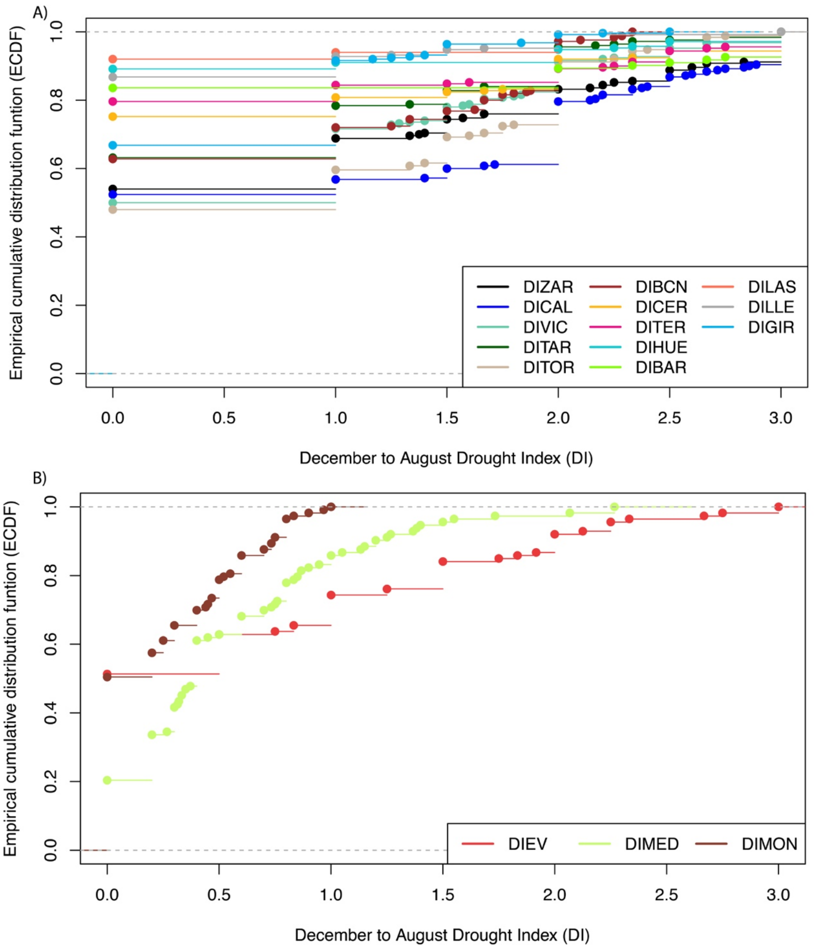

Figure 2. The empirical cumulative distribution function (ECDF), used to describe a sample of observations of a given variable. Its value at a given point is equal to the proportion of observations from the sample that are less than or equal to that point. ECDF performed for the local drought indices (A) and the regional drought indices (B).

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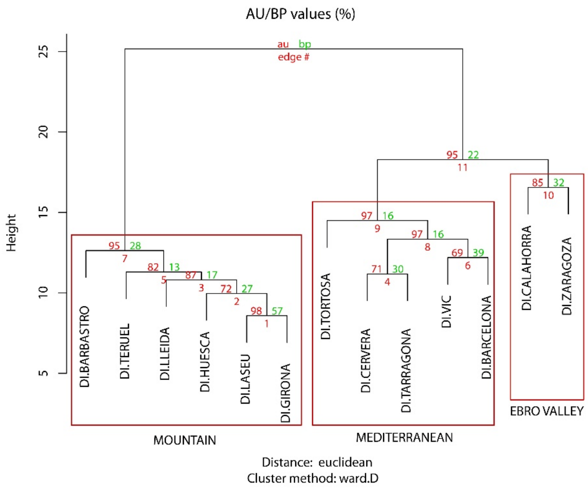
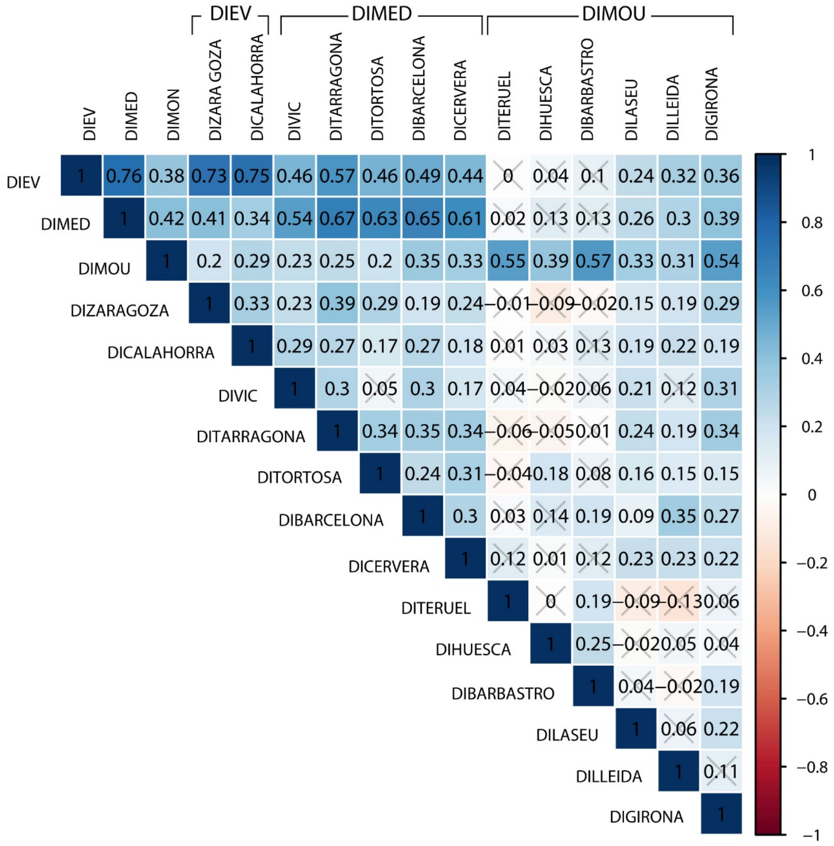


Figure 3. Dendrogram showing the hierarchical cluster analysis of the drought indices developed from the historical documents for each location. The AU (approximately unbiased *p-value*) is indicated in red and the BP (bootstrap probability) is presented in green.



	DIEV	DIMED	DIMON	DIZARA GOZA	DICALAHORRA	DIVIC	DITARRAGONA	DITORTOSA	DIBARCELONA	DICERVERA	DITERUEL	DIHUESCA	DIBARBASTRO	DILASEU	DILLEIDA	DIGIRONA
DIEV	1	0.76	0.38	0.73	0.75	0.46	0.57	0.46	0.49	0.44	0	0.04	0.1	0.24	0.32	0.36
DIMED		1	0.42	0.41	0.34	0.54	0.67	0.63	0.65	0.61	0.02	0.13	0.13	0.26	0.3	0.39
DIMOU			1	0.2	0.29	0.23	0.25	0.2	0.35	0.33	0.55	0.39	0.57	0.33	0.31	0.54
DIZARAGOZA				1	0.33	0.23	0.39	0.29	0.19	0.24	−0.01	−0.09	−0.02	0.15	0.19	0.29
DICALAHORRA					1	0.29	0.27	0.17	0.27	0.18	0.01	0.03	0.13	0.19	0.22	0.19
DIVIC						1	0.3	0.05	0.3	0.17	0.04	−0.02	0.06	0.21	0.12	0.31
DITARRAGONA							1	0.34	0.35	0.34	−0.06	−0.05	0.01	0.24	0.19	0.34
DITORTOSA								1	0.24	0.31	−0.04	0.18	0.08	0.16	0.15	0.15
DIBARCELONA									1	0.3	0.03	0.14	0.19	0.09	0.35	0.27
DICERVERA										1	0.12	0.01	0.12	0.23	0.23	0.22
DITERUEL											1	0	0.19	−0.09	−0.13	0.06
DIHUESCA												1	0.25	−0.02	0.05	0.04
DIBARBASTRO													1	0.04	−0.02	0.19
DILASEU														1	0.06	0.22
DILLEIDA															1	0.11
DIGIRONA																1

Figure 4. Correlation matrix (Spearman) between the individual drought indices and the cluster drought indices for the period of 1650-1899. Values are significant at $p<0.05$, except those marked with a gray cross, which are not significant.

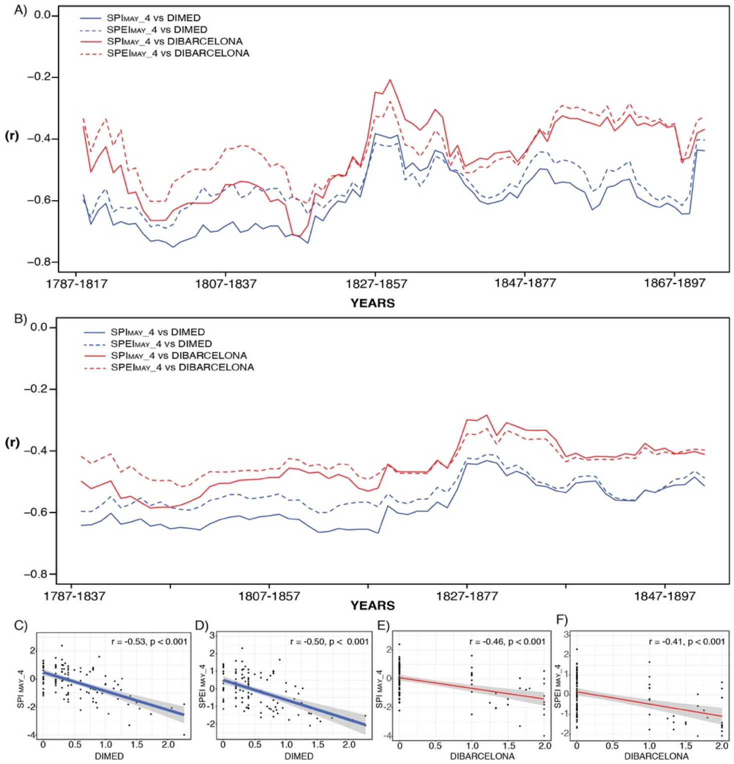
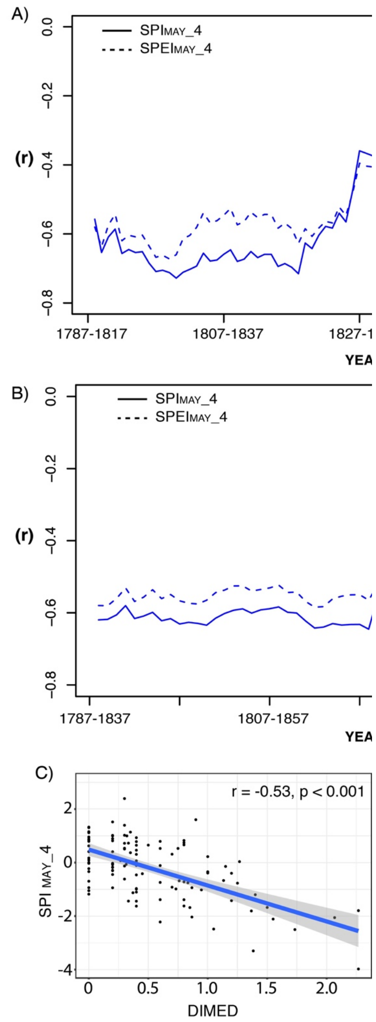


Figure 5. A) 30y moving correlation between DIMED, DIBARCELONA and the instrumental computed SPI and SPEI. B) Same but 50y moving correlations. C) Correlation (Spearman) between DIMED and SPI$_{MAY}$_4 for the full period (1787-1899). D) Correlation between DIMED and SPEI$_{MAY}$_4 for the full period (1787-1899). E) Correlation between DIBARCELONA and SPI$_{MAY}$_4 for the full period (1787-1899). F) Correlation between DIBARCELONA and SPEI$_{MAY}$_4 for the full period (1787-1899)



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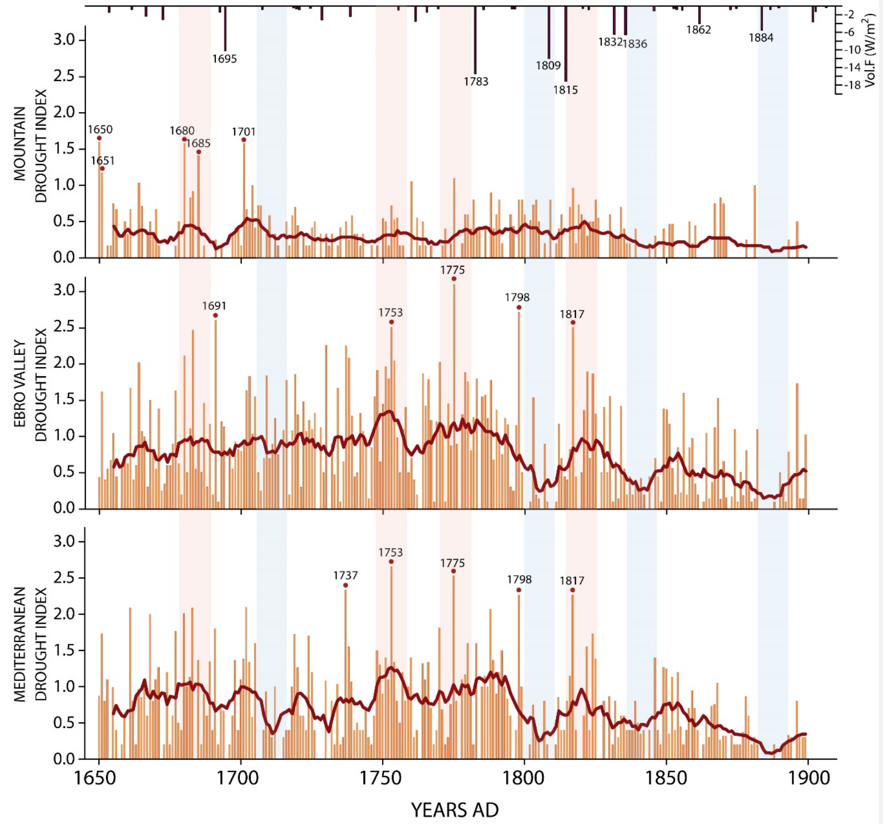

Figure 6. Drought indices of the three clusters, DIMOU (Mountain), DIEV (Ebro Valley) and DIMED (Mediterranean). Vertical orange bars represent the drought index magnitude, 0 denotes normal conditions, and 3 denotes an extreme drought year. The extreme drought index years are also highlighted with a red circle. Extreme volcanic events from Sigl et al., 2015, are shown in the top panel. Vertical pink shadows indicate extreme common (for all three clusters) drought periods, while blue shadows indicate common periods with fewer droughts.

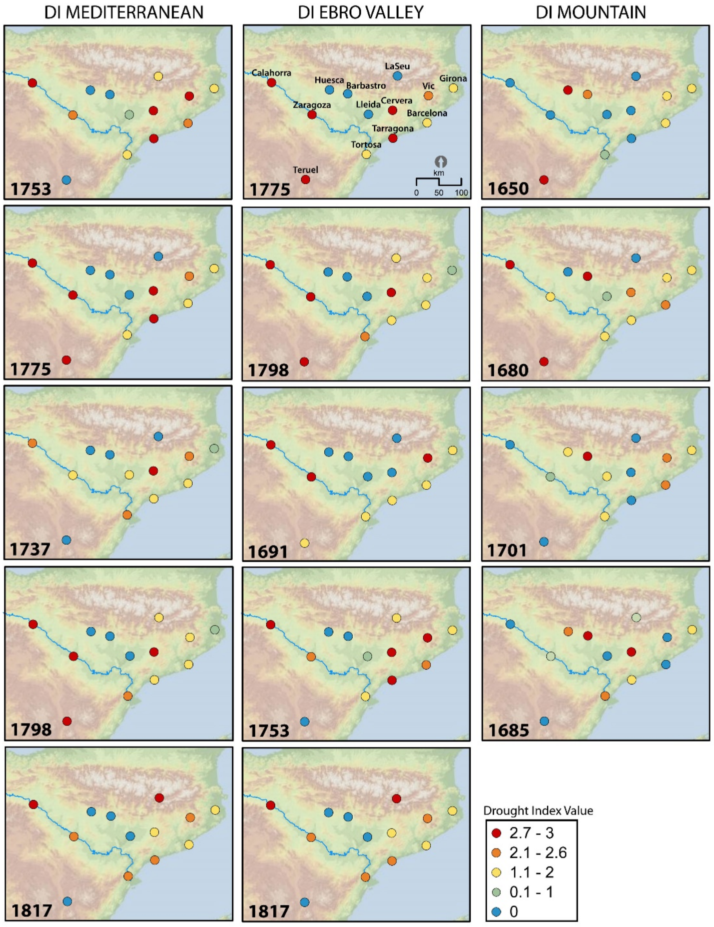

Figure 7. Spatial distribution of the most extreme drought years (based on the 99th percentile of the cluster drought indices). The distribution is ordered top-down. The drought index value (magnitude) for each site within the cluster is also represented.

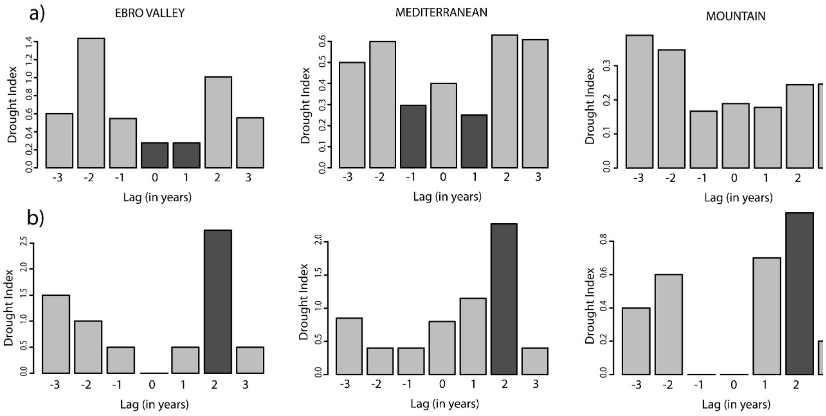

Figure 8. a) Superposed epoch analysis (SEA) of the three regional drought indices, DIMOU (Mountain), DIEV (Ebro Valley) and DIMED (Mediterranean), with major volcanic events from Sigl et al., 2015. Black shadows show significance at $p<0.05$, i.e., significantly lower or higher drought index values after the volcanic event. b) SEA of only the Tambora (1815) event showing a significant ($p<0.05$) increase in the drought index.

Level	Type of ceremony
0	No ceremonies
1	Petition within the church
2	Masses and processions with the intercessor within the church
3	Pilgrimage to the intercessor of other sanctuary or church

Table 2. Rogation levels according to the type of ceremony celebrated.