Dear editor, this is the point by point response with which we aim to respond to all the questions raised by the reviewers.

Reviewer 1.

I think that the authors have addressed only part of my previous concerns, but the core of the problems that I find have not been solved. Specially, I am not convinced by the application of the clustering technique to the indices generated by the authors.

Sorry for the misunderstanding, we did not apply the clustering technique to compute the indices but to evaluate similarities among local series. We clarify this in lines 231-233.

The indices are semi quantitative, continuous and nonlinear variables. I think that, under these conditions, the use of the cluster techniques is questionable. In the new version I do not find convincing arguments justifying this application. The inconsistency of the results reinforces this.

We do not agree with the reviewer on this point. We think that our results are not inconsistent. The drought indices inferred from low elevation sites show common patterns suggesting common climatic driving forces. In addition, the mountain environment drought indices show more local patterns and do not reflect as well the temporal patterns of the low elevation indices. The limitations on the use of rogations as climatic proxies is not related to the technique of the analysis as rogations in different environments reflect climate events that occur at different time scales.

Now, the authors emphasize the limitations in the DI Mountain cluster, whihc is Ok. However, I still think that it is a purely statistical artifact. I have provided different reasons I my previous reviews. On top of them, I provide an additional one. Figure 7 shows the spatial patterns of extreme drought years. 1685 and 1701 (bottom right panels of the figure) show that in these 'extreme' years of the mountain cluster, Teruel shows an index value of 0.

What is meant is that 1685 and 1701 cannot be considered as extreme drought years in Teruel. From the regional tree-ring width hydroclimate reconstruction near Teruel (Tejedor et al., 2016) we can see that both years were considered as 'normal'. This also means that the DI Mountain has a weaker and less robust physical meaning. We clearly stated this in the discussion and conclusion sections.

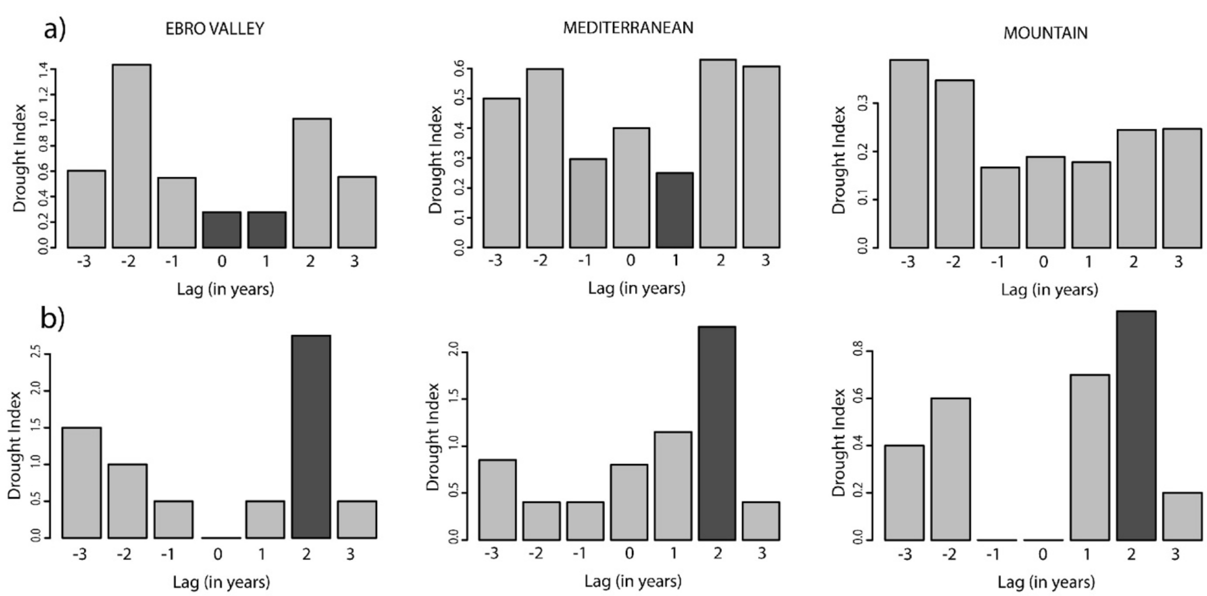
I think this is not acceptable and is another proof of the lack of physical foundation of this cluster analysis in an area of high precipitation and temperature variability, as acknowledged by the authors in lines 647-658.

We think we have detailed the potential drawbacks of the DI Mountain and the strengths and weaknesses of performing clustering techniques. Despite Teruel's high elevation (900 m.asl), the annual mean precipitation is fairly low (378 mm; AEMET, 2019). Nevertheless, the monthly precipitation varies with respect to that in the Ebro Valley, driven by convective storms during August, September and October. The strong precipitation and temperature variability are reflected in the individual DI clustered in the DI Mountain, including a weaker or less robust signal as opposed to the solid and neater DI Mediterranean and DI Ebro Valley (Figures 4 and 6). We do not see it as a lack of physical foundation of the cluster but as a reflection that rogation ceremonies in high-elevation environments had a greater variability and intensity through time than in the low lands and Mediterranean coast. Therefore, DI Mountain results must be treated with caution, as we stated in the manuscript, but that does not invalidate it.

The new version of the discussion is focused in justifying that rogation records are good proxies for droughts. This is has been proven in the literature and I am not questioning at all their value as local indicators of droughts.
We also demonstrate that in some areas (Ebro Valley and Mediterranean coast) rogation records are suitable proxies for droughts not only as local indicators but also at a regional scale, which we believe is a novel finding.

My point is on how the cluster is applied and interpreted in that specific case, not on the validity of rogations.
We did not apply the clustering technique to compute the indices but to evaluate similarities among local series (lines 231-233).

Panel a) of figure 8 is from my viewpoint another proof of lack of consistency. How can the authors explain that they find in the Mediterranean cluster a significant signal before the volcanic eruptions? (year -1) Do they have an explanation for this?.
There are still uncertainties on the dating of volcanic events from ice-cores. Here, we only include the largest events on ice-cores from Sigl et al., 2015, which improve the uncertainty of the dating with respect to Gao et al., 2008 or Crowley and Utterman, 2013. However, there are still events with dating issues of +- 1 years. Therefore, we have been more restrictive with the significant level, now adjusted to p<0.01.



I think that the only robust result is the impact of the Tambora eruption in panel b, a result previously reported in papers co-authored by some of the authors.

Although is true that a drought response was also found in Dominguez-Castro et al., 2012 after the Tambora event, the methodology, the sites and the extend of the results are different. The response to Tambora event is large and significant in the three indices, including the DI Mountain, thus reaffirming their validity as extreme droughts proxies, and at the same time proving the consistency of these results. Lines 598-617.

So, I do not think the paper is acceptable for publication.

Additional comments

- The authors claim that they have computed the SPEI index since 1787. This index requires instrumental data to compute the AED. Which data have they used? This should be explained in the text, since, as they claim, the only long instrumental series in the region is the Barcelona temperature series. Is this a combination of instrumental and proxy records?. If so, this must be carefully described in the text.

We calculated the SPEI with the SPEI package (Begueria et al., 2014). From the various ways of calculating evapotranspiration we chose Thornwaite, which requires only temperature and latitude as inputs. These details are included in lines 275-277.

We used the temperature and precipitation instrumental data from Prohom et al., 2012; 2015 that can be downloaded here;

http://www.meteo.cat/wpweb/climatologia/serveis-i-dades-climatiques/serie-climatica-historica-de-barcelona/

- The language needs further revision. I asked in my previous review but it does not seem to have been taken into account too seriously.

This has been completed. The manuscript was reviewed by a native English speaker.

- Some references are missing or wrong. Examples:

line 168 AEMET 2012 missing

Corrected.

line 744-745 I have not been able to find Dominguez-Castro and Garcia Herrera GRL 2016

Corrected.

The reference to Garcia-Ruiz 2001 about climate change impacts in the Medittarean should be updated. See for example

The climate of the Mediterranean region: from the past to the future

2012 , Elsevier Insights, 592pp, ISBN: 978-0-12-416042-2 , Ed. Lionello P.

Mediterranean Climate Variability

Done.

2006, Elsevier, Amsterdam, ISBN: 0-444-52170-4, 438 pp, Eds: Lionello P., P. Malanotte-Rizzoli and R. Boscolo

- DIMED appears in l 272, while its meaning is explained in line 324

Corrected.

Reviewer 3.- Reconsidered after major revisions

The manuscript is an interesting work on historical droughts in Northeast Iberian Peninsula, but in my opinion it needs some revisions before publishing:

Thank you for your comments.

1) In the literature you can find different definitions of the drought concept (atmospheric, meteorological, hydrological, agricultural), depending on the physical variable studied (relative humidity, rainfall, other elements of the hydrological cycle), and the duration of the event (days, months, seasons). I understand that here the authors are studying agricultural droughts, due to the origin of the data (rogations linked to agricultural production). In any case, it would be important to precise this point.

We appreciate your comment. However, it is difficult to determine one single type of drought. In cereals of long cycle, without any other artificial support, during the period of the year in which the harvest is in progress both the meteorological and the agricultural drought converge. The rogation was not only agronomical or focused on a drought or agricultural problem. They already inferred that the problem was meteorological. And they always asked for timely rain, appropriate rain, or consistent rain. Sometimes in despair they even asked that at least there be spray! In other words, they asked for the occurrence of a meteorological phenomenon. In consequence, the follow-up or sentinel that gives them information is agricultural, but their answer is by a meteorological anomaly, and they ask for the development of a normalized meteorology, that in consequence will allow a development of the appropriate agriculture. (Lines 199-206).

2) The nature of rogation ceremonies must be explained with more detail. For instance, is it possible to find a ‘preventive rogation’, that is, a ceremony organized before the event occur? In this sense, the date of the rogation is an important information. It may be the case that a dry winter provoked the rogation, but timely spring rainfalls yielded a good harvest. In that case, can we speak on ‘drought’? In relation to previous comment, perhaps here we could speak on dry winter (meteorological drought), but not on ‘agricultural drought’, and, in consequence, this event is not comparable with other characterized by the water deficit during an entire year.

Rogation ceremonies are a relatively new climatic proxy indicator. Most of the methodological details and criteria can be found in Martín-Vide & Barriendos (1995), and Barriendos (1997). "Preventive" rogation is a concept that indicates a first institutional response when drought is in an early stage of crop affectation meaning that; i) no damages are recorded, ii) cereal crop is showing first negative effects by drought, iii) any rainfall event can correct the drought.
Of course, a systematic record of dates for this and other rogation levels is important, in order to consider severity and duration of drought events.

Drought is a cumulative phenomenon. Then, as you comment, certainly a dry winter can give any "preventive" rogation of level 1 in early spring. In fact, drought in winter shows effects in agriculture during the next months. This affectation is recorded by the rogation system. Then, if drought is persistent during the following spring, rogation ceremonies convoked by institutions are increased to higher levels.
To answer your interesting question, if we would work just for economic or agricultural history, the truth is that this short drought would not exist, or it will not be considered because of absence of impact. However, in the context of climatic variability, any minor rogation convoked for a short event, even without impacts on agriculture, is recording a meteorological drought. In a similar way, instrumental records can show months or seasons with low values of precipitation, but cumulative yearly value can be normal if other months are rainier. If rogation proxies can detect a high-resolution event, we think this is an improvement on knowledge of climatic variability at different time scales.
Finally, we agree that the rogations system is a proxy developed within an agricultural framework (institutions monitoring crops) and thus the information available is in fact related to meteorological and agricultural droughts.

The 'annual' index (from December to August) may mask important intra-annual fluctuations, in my opinion it is preferable to divide the information into seasonal indices, following the different phases of the plant growing, from seed (autumn) to harvest (summer). In addition, all rogations are linked to cereal production? Other plants (fruits, olive trees) have different climatic limitations, and it would be possible that a single meteorological event (for instance, dry spring) was harmful for a specific plant, but not for another (for instance, the barley is more tolerant to drought than wheat).

This is a good remark. However, within the study area the main agricultural cereals are wheat and barley and are generally mixed i.e., cereal plots are mixed, and farmers usually do not focus on one single cereal but grow several. Therefore, in the study area there are not extensive areas that we can identified as of a single cereal. The greater agricultural homogeneity found in the Mediterranean and Ebro Valley might be one of the reasons of finding a common pattern. The greater specificity in mountain environment crops may be one of the causes of a weaker regional pattern.
In addition, when the traditional agriculture in the western Mediterranean is considered, the basic production of cereals were wheat and barley, and more specifically wheat. This was common practice beyond cultural, religious or political contexts. Bread is the basic food for most of the population during the Low Middle Age and Early Modern Epochs, as is indicated by historiography. It logically follows, then, that a permanent and complex monitoring system involving several public institutions (professionals, church, etc.) would focus on the most basic food production. Unfortunately, cultivation of other agricultural products does not have a similar monitoring system. To use other products for climatic proxies, we would have to collect information in an indirect way, such as from taxes statistics, tithes and other economic indicators. The reliability of the economic or tax information in Spain, however, is relatively low and irregular

due to the usual practice of farmers to hide it. We do not include such information in the manuscript.

3) I have doubts on the classification of the rogations (lines 205-207, Table 2). Were the ceremonies the same in all the cities and during the whole time period, from 1650 to 1899?

Yes. From our direct reading of historical archives, we can state that institutional controls in pre-industrial society were so strict that many elements didn't change for centuries. We have added information in the discussion, lines 503 to 519.

Nevertheless, the institutional controls in pre-industrial society were so strict that many of its constituent parts remained unchanged for centuries, and rogation ceremonies are one such element. This can be explained by two different factors. First, rogation ceremonies are used within the framework of the Roman Church Liturgy, so changes can only be defined and ordered by the Vatican authorities. If there is a will to change criteria affecting the substance of liturgical ceremonies, all involved institutions must record considerations, petitions and decisions in official documents from official meetings, supported by public notaries. In addition, changes must be motivated from the highest institutional level (Pope) to the regional authorities (Bishops) and local institutions (Chapters, parishes...). This system was too complex to favor changes. A second mechanism guarantees the stability of the rogation system: if any minor or important change in rogations is instigated at local level by the population or local institutions, this interference directly affected the Roman Church Liturgy. However, it was a change not to be taken lightly as the Inquisition Court would start judicial proceedings, and could bring a criminal charge of heresy. The punishment was so hard that neither institutions nor the people were interested in introducing changes in rogations.

Severity indices are based on the type of ceremony, but is it a reliable criteria? In the discussion (lines 404-411), authors say that '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 level 3 has to be necessarily equivalent'. In that case, how must we interpret these indices? In my opinion, these indices only specify the nature of the ceremonies organized as response to natural hazards, but do not inform on the severity of the climatic event. In consequence, what is their utility from a climatic point of view? In my opinion, the binomial distribution (occurrence or not) is the more appropriate statistical approach to the treatment of this information.

The mechanisms underlying the triggering or absence of a rogation ceremony have been widely discussed in Barriendos et al., 1997; 2005 in Vicente-Serrano and Cuadrat, 2007 or even under the framework of a European funded project (Domínguez-Castro et al., 2012). The rogation ceremonies are indirect sources of climatic extreme events. The different types of rogations have a progressive meaning of climatic stress. For example, when a rogation of level 3 is performed, it means that the previous efforts of the society, municipal authorities and the church performing rogations of level 1 or 2 have not yielded results i.e. useful precipitation. Using a quantitative index such as the SPI, we could identify, for instance, droughts with an index of -2 and argued that those are twice as intense as those with an index of -1. However, here we cannot argue, unlike with other quantitative indices like the SPI, that a drought classified with level 2 is twice as intense as one with level 1. Yet, we can infer with high confidence that if there was a drought of level 2 it is because those types of ceremonies of level 1 did not work, and therefore the drought was still an issue for the development of the crops i.e., there is a progressive drying, but it does not have to be twice as intense. With this modified paragraph (lines 531-542) we tried to be honest with the semi-quantitative nature of our data and thus explain the potential drawbacks.

In addition, we are trying to evaluate the spatial scope of the rogations as a climate proxy. We also perform a comparative analysis of the local series in an attempt to construct regional series (in which the local binomial character is modified). For a local analysis, the occurrence may or may not be the most appropriate technique. For our attempt to regionalize, the approach proposed (and widely discussed) is justified. Finally, the transformation from categorical to semi quantitative values considers the incorporation of uncertainties, widely discussed in the text. Despite this potential loss of precision, our results show common and consistent patterns on a regional scale (Mediterranean and Ebro Valley). Not included in the manuscript.

4) Clustering is an appropriate tool to classify and group local series into regional series. There are very different clustering algorithms, hierarchical and not hierarchical. Why have you used Ward method with Euclidean distance, and not, for example, the non-hierarchical k-means, or other methods as the principal component analysis? Results of clustering must yield groups more or less homogeneous, but the chosen number of clusters is normally arbitrary. Why do you distinguish between Mediterranean and Ebro Valley group (dendrogram, Figure 3), if, as you say (lines 450-451) 'the high correlation between DIEV and DIMED is suggesting similar climatic characteristics'?

We know from observations that, although DIEV and DIMED locations have similar climatic characteristics, the Mediterranean coast locations have slightly higher precipitation totals. Then, we tried to differentiate that by developing two drought indices, which is supported by the cluster. One is reflecting the Ebro Valley conditions and the other is reflecting a more Mediterranean-like climate. Therefore, our final grouping is not only statistically significant, but it has also a geographical/physical meaning. Included in lines 428-429.

5) Validation of the regional drought indices is made using the overlapping period 1786-1899 between documentary and instrumental data. But, as you say in the discussion (lines 390-392) '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'. I would add changes in the socioeconomic structures, organization of the cereal production, agricultural techniques, etc. In consequence, this period is not valid to calibrate and/or validate the rogation series in previous centuries. The cultural background, economic organization and technology of the 19th century was not the same that in previous centuries, and calibrations established for 19th century are not applicable to 17th century! In fact, you do not use this calibration (regression in Figure 5) to interpret previous data, only to validate the index during the 19th century.

We partially agree with this comment. It is true that there were changes in society and the political sphere but when there was an intense drought, the mechanism the society had to prevent it was still performing rogation ceremonies. That is also validated by the high correlation with the instrumental series. Additionally, the calibration period begins in 1787 when rogations were still deeply established in the society. We could show how internal historiographic criteria is applied to this manuscript, but we consider it is beyond the scope of the main message of the manuscript.
In any case, it is true that after 1834, when the Inquisition Court was abolished, liberal and democratic movements arrived from Europe and Spain experienced a strong process of anticlericalism, including a certain loss of religious values. This process obviously affected the occurrence of rogations and respective records on documentary series of public institutions. Still, this affirmation is valid only for specific areas or social contexts, because history is complex, non-linear and the development was not homogenous.

Besides, this analysis is only made for DIMED (Barcelona), and not for the other points in the studied area. I suggest to remove this analysis (and the Figure 5).
The analysis is performed for both DIMED and DI Barcelona included in DIMED, showing similar results and consistency through time. This analysis was a specific request by one of the reviewers, and we believe is highlighting the validity of the derived drought indices where we have instrumental data. Even with all the potential uncertainties, this comparison is one of the few forms of validation of this type of information given the absence of overlap with instrumental series. We prefer to keep it as is.

6) Superposed epoch analysis (SEA). Although you give a reference, a brief explanation on the basis and procedures of this method would be important.
Done. See lines 293-308.

7) Minor questions:
Line 301:'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…' Erratum, I suppose, clustering is made using the period 1650-1770, common to all the stations, although the classification obtained is after applied to the complete period until 1899.
Sorry for the misunderstanding. As indicated in the methods, the cluster is made using the period 1650-1770. We have corrected this (lines 328-330).

Lines 373-375: 'However, two years after the Tambora eruption in April 1815, there was a significant ($p<0.05$) increase in the three drought indices…' However? The time life of volcanic aerosols in the atmosphere is around one to two years. The Tambora aerosols caused a radiative forcing of the global climate system of about 5.6W/m2 for one to two years following the eruption (Brönnimann and Krämer, 2016). In consequence, this increase in the drought indices may be caused not by the volcanic eruption, but by the return to 'normal' conditions (or not forced climate variability).
The hydroclimatic volcanic response has been recently study using tree-ring records from Europe (Gao and Gao, 2017; Rao et al., 2017), showing a persistent drying in southern Europe two years

after the volcanic event, which is consistent with our results. In addition, a previous study with rogation ceremonies (Dominguez-Castro et al., 2012), also highlights the year 1817 as one of the driest and it is attributed by the climatic effects induced by the Tambora event. All of which is considered in the results (lines 397-405) and discussion (lines 598-617) sections.

Lines 417-418: ‘the local series are compared with the regional reference series as a basic element of quality control’. But, if the regional series is obtained from the average of local series, here we have a circularity problem.
We appreciate your concern. To solve it, we performed a modified version of the leave-one-out calibration method. Both the SPI and the SPEI are then correlated with a DIMED version that excludes an individual DI each time. The results are shown in the figure below (now Figure S1). We found significant correlations ($p<0.001$) on each case, including correlations above 0.45. We believe this example clearly shows that we do not have a circularity problem. We now include this in the methodology (lines 282-83) and in the results (367-369), and as Supplementary Figure 1.

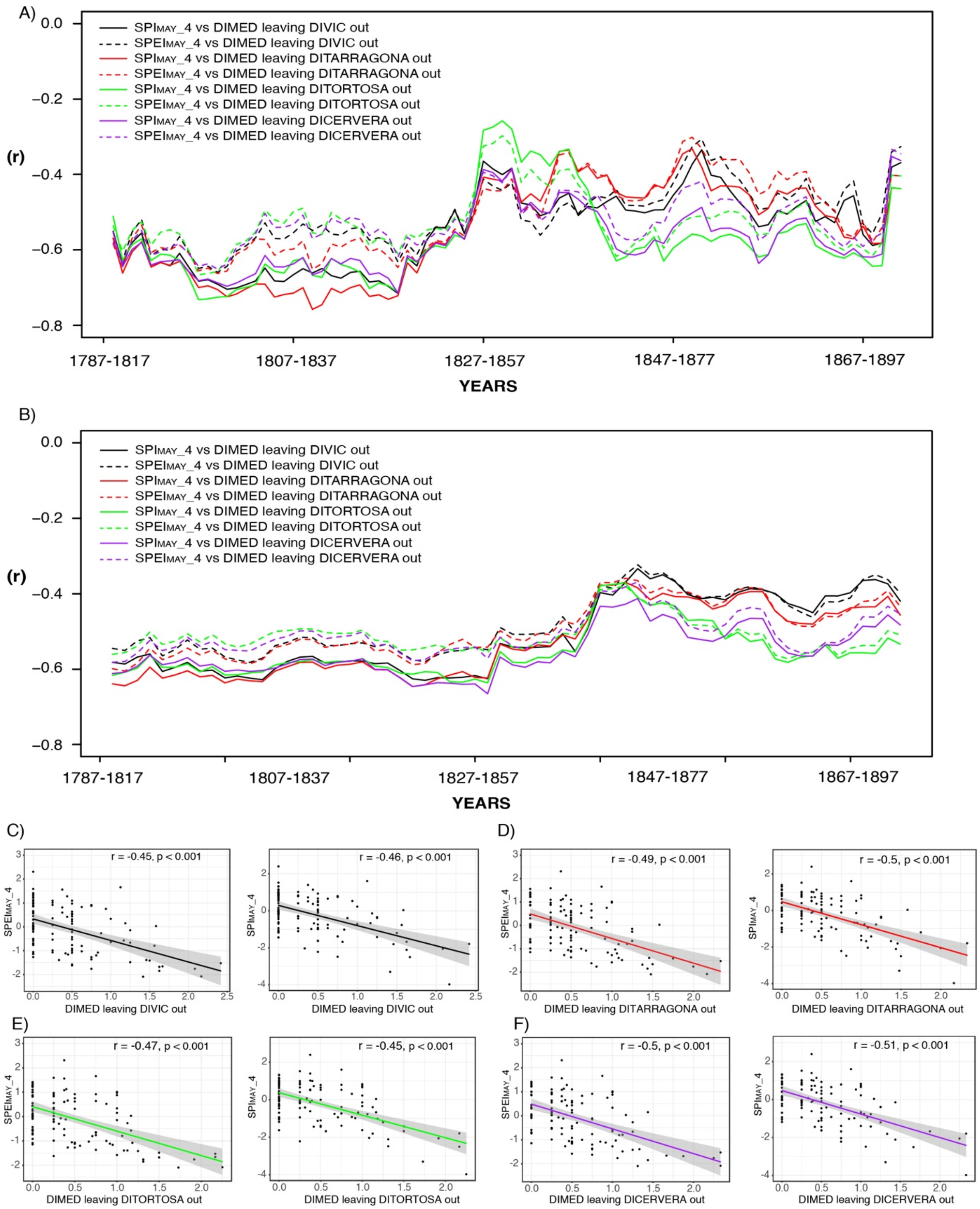


Figure S1. A) 30y moving correlation between a DIMED version leaving one out and the instrumental computed SPI and SPEI. B) Same but 50y moving correlations. C) Correlation (Spearman) between DIMED leaving DIVIC out and SPIMAY_4, and SPEIMAY_4 for the full period

(1787-1899). D) Correlation between DIMED leaving DITARRAGONA out and SPIMAY_4, and SPEIMAY_4 for the full period (1787-1899). E) Correlation between DIMED leaving DITORTOSA out and SPIMAY_4, and SPEIMAY_4 for the full period (1787-1899). F) Correlation between DIMED leaving DICERVERA out and SPIMAY_4, and SPEIMAY_4 for the full period (1787-1899).

Line 432: 'the local series are separated by tens or hundreds of kilometers'. If you speak on meteorological droughts, this is not a problem, because the dynamical conditions provoking dry conditions are associated to the predominance of anticyclonic conditions, and the spatial extension of an anticyclone may be much greater. Again, we are speaking on the drought concept. Meteorological, hydrological, agricultural?
We appreciate your comment. We clarified that we are indeed talking about a drought that links various characteristics of meteorological and hydrological drought to agricultural impacts. In any case, a recent study on the major drought episodes on Spain (González-Hidalgo et al., 2018) shows that there are some persistent droughts affecting large areas of Spanish mainland, including the mountain areas, associated to the predominance of anticyclonic conditions. However, in general, the spatial extent of droughts includes a great variability due to multiple factors (not included in the manuscript).

Figure 5. Significance level must be added in the figures. D), E), F), correlation is the Pearson correlation coefficient?
We appreciate the suggestions. However, we already included the significant level together with the Spearman correlation in the latest version of the manuscript. Again, we believe the reviewers did not get the latest version of the manuscript. We are sorry for that. It is the Spearman correlation as stated in the caption.

Figure 7. The legend is arbitrary, why do you distinguish between 2.1-2.6 and 2.7-3 DI values?
The legend was based in percentiles. Now we include it in the caption.

Reference
Brönnimann S, Krämer D. 2016. Tambora and the 'Year Without a Summer' of 1816. A perspective on Earth and Human Systems Science. Geographica Bernensia G90, 48 pp, doi:10.4480/GB2016.690.01

Reviewer 4. Accepted subject to minor revisions.
Rogation ceremonies: key to understand past drought variability in northeastern Spain since 1650. This study compiles and quantitatively analyses drought indices derived from documentary data on rogation ceremonies in northeastern Spain to further insights into historical droughts but also to understand the role of volcanic forcing on past event.
The most importantly contribution of the paper is that it provides a very interesting insight into both the strengths and weaknesses of documentary sources, especially approaches that seek to

derive quantitative estimates from qualitative data. It is my view that the paper should be accepted following minor revision.

Many thanks for your positive comments and constructive review.

I suggest some points below that that the authors need to address. Most of my comments seek clarity and explanation. I also request the authors to give the paper a thorough edit. There are instances of misspelling or improper English scattered throughout the paper. This deserves considerable attention. There are also instances of long tracts of text that make it hard for the reader to track key points. Please use paragraphs more effectively to deal with this. There are also very long sentences at times (e.g. end of introduction) that need to be broken up.

Done.

I would like to know more about the documentary sources consulted. We don't get to know much about this aspect despite so much interpretation later depending on these sources. In line with comments from previous reviewers the original sources and their consultation/analysis needs to be given greater attention in the paper.

We provided detailed information about the documentary sources in the supplementary documents-Table S1. We have now moved that into Table 2.
In any case, a complete relation of documentary sources consulted requires an enormous display of pages of references. Case by case, each document can take hundreds of pages. A summary (as displayed now in Table 2) quantifying the collected sources is usually accepted. The main issue in displaying our effort is because we worked with primary sources, such as the administrative documentary sources, where every location usually contains 400-600 volumes of manuscripts. Rogations and other climatic descriptions are contained into these documentary series. Making a reference for every case would imply producing a book of references, which is not practical considering present editorial criteria. Users must be confident we work with all the quality requirements to preserve traceability of all the information used into the present manuscript.

The key methodological steps in the paper are as follows:

1) Development of a semi-quantitative series from qualitative data derived from documentary sources on rogation ceremonies. This is done using an established technique. I have no concerns to note.

2) Clustering of series to develop regional drought indices

This again seems to follow best practice. Importantly the analysis is not entirely statistically based and physical reasoning around the derived clusters is given. This is important as such techniques are somewhat subjective and the authors are transparent in their choices. The limitations of the approach are clearly articulated in the discussion.

3) Validation of the resultant series against instrumental records.

4) The performance of an epoch analysis to detect volcanic influence on historical droughts. This section is given the least attention in methods and most prominence in the abstract. I think that the authors need to explain this approach in more and sufficient detail to allow reader fully understand what they are doing here. A short paragraph should suffice. Why this method and what are the assumptions/strengths/weaknesses around the approach and desired attribution statements.

Many thanks for highlighting the merits of the manuscript. We now include a more detail section on the superposed epoch analysis (lines 294-308) and strengths/weaknesses are addressed in the discussion section.

I do not have local knowledge of the region but I find the results interesting, especially for the mountainous region. It seems the other two regions show similar results that are coherent with findings from previous studies. Indeed in discussion this aspect of the coherence of results needs to be moved further up. This is important information to have before getting into the limitations. Thanks for this suggestion, we now moved it further up.

I find the weaker results from the mountain region interesting. Some effort is expended on trying to explain why this difference and at times the authors get into attributing different processes. First, is this something seen in recent times when we have measurements?

This is an interesting point and the answer is not straightforward. First, the social and agrarian political system changed drastically during the first third of the 20th century with the construction of reservoirs. Both the Ebro Valley and much of the Catalan coast are flanked by two large mountain systems, the Pyrenees to the north, and the Iberian system from northwest to southeast. It is in these mountains where the highest rainfall occurs and therefore where the reservoirs are located. The ability to manage water resources became a determining factor for the local agriculture, which little by little began to generate more irrigated agricultural lands and less rain-fed agriculture. Second, in situations of anticyclonic stability that prevent the arrival of fronts loaded with humidity in the Ebro Valley, there are frequent convective storms in the Pyrenees and in the Iberian System. Although is true that most of the instrumental stations in Spain are located under 1,000 masl, we now know from observations that mountain regions are less affected by droughts than the lowlands. As noted above, there is a recent study on the major drought episodes on Spain (González-Hidalgo et al., 2018) showing that there are some persistent droughts affecting large areas of Spanish mainland, including the mountain areas. However, in general, the spatial extent of droughts includes a great variability (not included in the manuscript).

Second, given that the performance of a rogation was done based in part on the wishes of agricultural institutions, is there a risk that mountainous regions would have weaker political power in influencing rogations. Therefore, the lack of intense droughts in mountainous region or the disagreement with other regions, may be due to its weaker economic importance rather than anything to do with drought directly? I think the authors need to mention this possibility.

Your comment is very appropriated and well-focused. This argument could be negative for rogations in mountainous areas. But the rogation ceremonies system was not organized in a hierarchical structure, meaning that solicitudes were not sent to urban areas in lowlands, bishop authorities, or other administrations. Rogation ceremonies were not decided or prioritized from a distance. In fact, rogations ceremonies were adjusted to the capacities of every local community. This system is adapted to produce quick and efficient responses from local ecclesiastical authorities to local civil authorities, assessed by agricultural associations. The main idea of rogations is that after the first warning, the celebration of a rogation will be held within the next 4-6 days.

With the present manuscript and other works in progress, we are able to distinguish different climatic variabilities, confirming possible singularities in mountain areas. Rogation ceremonies help in this approach, because they can detect a range of climatic change from local sensitivities to large scale regional events or even global processes (such as volcanic events) (not included in the manuscript).

I also think that the authors could make more of the issues they run into for the mountainous region as a case of the challenges of using documentary sources. This needs to be mentioned in the abstract as its lessons are important for other studies.
Done.

The authors rightly state that the drought index for the mountainous region should be treated with extreme caution.
Thank you for your considerations. That is what we try to express in the revised version.

Need to be careful of tense used in abstract.
Done.

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Rogation ceremonies: A key to understanding past drought variability in north-eastern Spain since 1650

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ABSTRACT

In the northeast of the Iberian Peninsula, drought recurrence, intensity, persistence and spatial variability have mainly been studied by using instrumental data covering the past ca. 60 years. Fewer studies have reconstructed drought occurrence and variability for the pre-instrumental period using documentary evidence and natural proxies. In this study, we compiled a unique dataset of rogation ceremonies - religious acts asking God for rain - from 13 cities in the north-east 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 semi-quantitative, 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), where we discovered a highly significant and stable correlation with the Standard Precipitation Drought Index of May with a 4-month lag (r=-0.46 and r=-0.53; p<0.001, respectively), thus confirming the validity of the local and regional Drought Indices derived from the historical documents as drought proxies. On the other hand, the Mountain Drought Index presents various limitations and its interpretation must be treated with caution. 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 atmospheric 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 reduction in surface temperatures and, consequently, the higher availability of water that increases soil moisture. In addition, we discovered a common and significant drought response in the three regional drought indices two years after the Tambora volcanic eruption. Documented information on rogations thus contains important independent evidence 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 often lasts 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 give significant cause for concern. Spain is one of the European countries with a large risk of drought caused by high temporal and spatial variability in the distribution of 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).

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In other European regions, drought intensity and frequency have been widely studied, since their socio-economic and environmental impacts are expected to worsen with climate change (e.g. Spinoni et al., 2018; Hanel et al., 2018). Long-term studies using instrumental meteorological observations have helped in 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 multi-centennial long-term perspective in Europe by developing high-resolution drought indices derived mostly from tree-ring records (e.g. Büntgen et al., 2010, 2011; Cook et al., 2015; Dobrovolný et al. 2018). Finally, documentary records utilized in historical climatology have complemented the understanding of droughts across Europe (e.g. Brázdil et al., 2005, 2010, 2018). These studies, covering the last few centuries, usually focus on specific periods of extreme droughts and their societal impacts (e.g. Diodato and Bellochi, 2011; Domínguez-Castro et al., 2012) and yet, studies attempting to develop continuous drought indices for the last few centuries, inferred from documentary evidence, remain an exception (e.g. Brázdil et al., 2013, 2018; Dobrovolný et al. 2015a,b, 2019).

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In the Iberian Peninsula, natural archives including tree-ring chronologies, lake sediments and speleothems have been used to deduce 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.,

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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 large amount of documentary-based data with a good degree of continuity and homogeneity for many areas, which enables important paleo climate information to be derived 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 north-eastern Spain, the most important cities were located on the riverbanks of the Ebro Valley, which were surrounded by large areas of cropland (Fig. 1). Bad wheat and barley harvests triggered socio-economic impacts, including the impoverishment or malnutrition of whole families, 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, and is related to the nature and magnitude of the drought and the 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 believed in the will of God and the church to provide them with better harvests. They asked God to stop or provide 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 deliberation and decision-making by local city councils (Barriendos, 2005). Rogations are solemn petitions by believers asking God to grant specific requests (Barriendos 1996, 1997). Then, *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 rain causing crop failures and floods. In the Mediterranean basin, the loss of crops triggered severe socio-economic problems 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

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duration and severity of natural phenomena that stressed society is reflected in the different levels of liturgical ceremonies that were applied (e.g. Martin-Vide and Barriendos, 1995; Barriendos, 1997; 2005). Through these studies, we learned that the present heterogeneity of drought patterns in Spain also occurred over the past few centuries, in terms of the spatial differences, severity and duration of the events (Martin-Vide, 2001, Vicente-Serrano 2006b). However, the fact that no compilation has been made of the main historical document datasets assembled over the past several years is impeding the creation of a continuous record of drought recurrences and intensities in the north-east 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). The cities cover a wide range of elevations from Barcelona, which is near the sea (9 m a.s.l.), to 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 that analyzes all existing information for north-eastern Spain, including new, unpublished data for Huesca (1557-1860 AD) and Barbastro (1646-1925 AD) and examines the 13 sites jointly over a period of 250 years (1650-1899 AD). We analyzed droughts across the sites and identified extreme drought years and common periods in frequency and intensity. We also analyzed 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 north-eastern 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 separating the two (Fig. 1). The Ebro Valley has an average altitude of 200 m a.s.l. and its climate can be characterized as Mediterranean-type, with warm summers, cold winters and continental characteristics increasing with distance inland. Certain geographic aspects determine its climatic characteristics; for example, several mountain 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 (Serrano-Notivoli et al., 2017). 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, the barrier effect of the most frequent humid air masses causes gradually higher aridity towards the east and south (Vicente-Serrano, 2005; López-Moreno & Vicente-Serrano, 2007). Areas above 2000 m a.s.l. receive

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approximately 2,000 mm of precipitation annually, increasing to 2,500 mm in the highest peaks of the mountain range (García-Ruiz, et al., 2001). Annual precipitation in the Mediterranean coast is higher than that in the central 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 a 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. 2). These historical documents are the rogation ceremonies reported in the 'Actas Capitulares' of the municipal archives or main cathedrals. The documents (described in Table 2) range 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 were not only religious acts but also 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. The municipal authorities would then recognize the predicament and discuss the advisability of holding a rogation ceremony. Whether a rogation was celebrated or not was not arbitrary, since the cost was paid from the public coffers. When the municipal authorities decided to hold a rogation, the order was communicated to the religious authorities, who placed it on the calendar of religious celebrations and organized and announced the event. 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 others were held during the period of crop growth (March-May) and harvesting (June-August), since the socio-economic consequences when the harvest was poor were more evident at those times. Thus, it is reasonable to view rogations in an index from December to August. Finally, from the various types of droughts, we will be referring to a combination between meteorological and agricultural droughts. The rogation was not only agronomical or focused on a drought or agricultural problem. They already inferred that the problem was meteorological and therefore they always asked for timely rain, appropriate rain, or consistent rain. In other words, they asked for the occurrence of a meteorological phenomenon. In consequence, the follow-up or sentinel that gives them information is agricultural, but their answer is by a meteorological anomaly, and they ask for the development of a normalized meteorology, that in consequence will allow a development of the appropriate agriculture.

The qualitative information contained in the rogations was transformed into a semi-quantitative, 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 uniform ceremonies performed throughout the Catholic territories and

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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. 3). 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 cover the full period. A continuous drought index (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 chosen. The annual DI values were obtained by determining the weighted average of the number of levels 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 semi-quantitative 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 evaluate similarities among local stations, 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 a cluster analysis (CA) is that it allows similar data to be grouped together, which helps to identify 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 squares 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). Next, the root of the square difference between co-ordinates of a pair of objects was computed with its Euclidian distance. Finally, for each cluster within the hierarchical clustering, quantities called p-values were calculated via multiscale bootstrap resampling (1000 times). Bootstrapping techniques do not require assumptions such as normality in original data (Efron, 1979) and thus represent a suitable approach to the semi-quantitative characteristics of drought indices (DI) derived from historical documents. The *p-value* of a cluster is 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

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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 $Regional\ Drought\ Index\ (x) = (x_1 + x_2 + x_3 \ldots)/n$

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

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

To better understand the relationship between the derived 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 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 contains coherent regional information from a Mediterranean section similar to our regional drought indices stations located along the Mediterranean coast. We then calculated the Standardized Precipitation Index (SPI, McKee et a., 1993) and the Standardized Evapotranspiration and Precipitation Index (SPEI, Vicente-Serrano et al., 2010). SPEI was calculated with the R Package 'SPEI' (Begueria et al., 2014). From the various ways of calculating evapotranspiration we chose Thornwaite, which only requires temperature and latitude as input. Next, we calculated the Spearman correlation between the drought indices of the Mediterranean coast and the SPI/SPEI at different time scales including a maximum lag of 12 months covering the period 1787-1899. Further exploration of the relationship between the drought indices inferred from historical documents and the instrumental drought indices through time, were performed by 30- and 50-year moving correlations. Finally, to avoid the circularity problem we performed the same analysis leaving one local station out each time.

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

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To identify the extreme drought years, we selected those 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 method involves sorting data into categories dependent on a key-date (volcanic events).

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For each category, the year of the eruption is assigned as year 0, and we selected the values of the drought indices for the three years prior to the eruption and three years following in order to obtain a SEA matrix (number of volcanic events multiplied by 7). For each particular event, the anomalies with respect to the pre-eruption average were calculated to obtain a composite with all the events for the 7 years. Statistical significance of the SEA was tested by a Monte-Carlo simulation based on the null hypothesis of finding no association between the eruptions and the climatic variables studied. Random years are chosen for each category as pseudo-event years, and the average values are calculated for -3 to +3, the same as for real eruptions. This process is repeated to create 10,000 randomly-generated composite matrices, which are sorted, and a random composite distribution is created for each column in the matrix (i.e. year relative to the eruption year 0). The distributions are then used to statistically compare the extent to which the existing composites are anomalous. We used these distributions to test the significance of the actual composites at a 99% confidence level. The largest volcanic eruptive episodes (Sigl et al., 2015) 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 a drought index for each location in NE Spain from 1650 to 1899 AD

We converted the ordinal data into continuous semi-quantitative index data by performing a weighted average of the monthly data (see methods). As a result, we developed an annual drought index (from the previous December to the current August) containing continuous values from 0 to 3 collected from information on the annual mean extreme droughts of each year for each of the 13 locations. The empirical cumulative distribution function (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 (Fig.2B). 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.

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 and after applied to the complete period until 1899 revealed three significant and physically coherent areas, hereafter known as Mountain, Mediterranean and Ebro Valley (Fig. 3). The first cluster includes cities with a similar 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

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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), comprising Zaragoza and Calahorra. The resulting drought indices in regional DI series can also vary from 0 to 3, but show a relatively continuous distribution range (Figure 2B).

The Spearman correlation matrix for the period 1650-1899 AD confirms the high and significant ($p<0.05$) correlations between each individual DI and its corresponding group, confirming 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 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, individual DIs compared one to another reveal some correlation values not to be significant ($p<0.05$).

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

The highest 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) was found for the SPI of May with a lag of 4 months (SPI_{MAY_4} hereafter). A slightly lower, though still significant correlation was obtained from the SPEI of May with a lag of 4 months ($SPEI_{MAY\_4}$) (r=-0.41; $p<0.001$, Fig.5D). The regional Mediterranean 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) presented higher and more stable correlations through the full period than with DIBARCELONA. The relationship with the $SPEI_{MAY\_4}$ was also high and stable throughout the overlapping period, although lower than with SPI_{MAY_4}. Furthermore, when the analysis was performed leaving one station out each time (Fig. S1), the results remain significant ($p<0.001$) and the correlation in all cases is above 0.45. 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.

3.4. Detecting extreme drought years and periods in the north-east 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

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(DIEV) had the highest number of droughts (derived from the highest number of positive index values) followed by the third region (Mediterranean DI, DIMED). The 17th and 18th centuries exhibited a relatively large number of severe droughts (Fig. 6). High positive index values over the duration of the DIs in all three series indicate that a drought period occurred from 1740 to 1755 AD. The lowest DIs were found at the end of the 19th century, meaning that droughts were less frequent in this period. 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 drought-free. 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 ceremonies were needed.

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), and 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).

We performed a superposed epoch analysis (SEA, see methods) to study the drought response over north-east Iberia to major volcanic eruptions (Fig. 8a). The figure shows significant decreases ($\rho<0.05$) in the Ebro Valley and Mediterranean DI values during the year a volcanic event occurred and for the following year. 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 ones. 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).

4. Discussion

In this project, we were aware of the potential drawbacks and dealt with the problem of analyzing the spatial representativeness of the rogation series through a cluster analysis. We thus identified 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. However, 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

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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 suggests similar climatic characteristics. Furthermore, the main cities among these two clusters share similar agrarian and political structures that support the comparison. Still, we know from observations that, although DIEV and DIMED locations have similar climatic characteristics, the Mediterranean coast locations have slightly higher precipitation totals, which is supported by the cluster. One is reflecting the Ebro Valley conditions and the other is reflecting a more Mediterranean-like climate. Therefore, our final grouping is not only statistically significant, but it has also a geographical/physical meaning.

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 that the productive system of the mountain areas is not only based on agriculture, but also on animal husbandry, giving them an additional resource for survival in cases of extreme drought. Therefore, the DIMOU cluster might not only be collecting climatic information but also diverse agricultural practices or even species, translated into a weaker regional common pattern. For instance, Cervera and Lleida share similar annual precipitation totals, but belong to the Mediterranean and the Mountain Drought Indices respectively. Lleida is located in a valley with an artificial irrigation system since the Muslim period, which is fed by the river Segre (one of the largest tributaries to the Ebro river). The drought in the Pyrenees is connected with a shortage of water for the production of energy in the mills, as well as to satisfy irrigated agriculture. However, the irrigation system itself allowed Lleida to manage the resource and hold out much longer. Therefore, only the most severe droughts, and even those in an attenuated form, were perceived in the city. Cervera, located in the Mediterranean mountains, in the so-called pre-littoral system and its foothills, has a different precipitation dynamic that is more sensitive to the arrival of humid air from the Mediterranean. In addition, Lleida had a robust irrigation system that Cervera did not have. The droughts in Cervera are more akin to the "Mediterranean" ones and thus its presence in the Mediterranean Drought Index seems to be consistent.

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 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 and valuable as drought proxies (e.g. Tejedor et al., 2016; 2017c). The consistency of the clusters in the Ebro Valley and the coastal zones (DIMED and DIEV) is especially encouraging and reflects the high potential of rogations as a drought proxy. It is precisely in these areas that there are no relict forests, due to human intervention, and therefore no centennial tree-ring reconstructions can be performed to infer past climates.

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Consequently, in these environments, the information from historical documents is especially relevant.

Confirmation of 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 in the 19th century, whereas instrumental weather data generally begins 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 have been calibrated with such a long instrumental period. The correlation is maximized in May, the key month for the harvest to develop properly. In addition, the 4-month lag confirms the importance of the end of winter and spring precipitation for good crop growth. The high DIMED correlation ($r=-0.53$; $p<0.001$) indicates not only that this cluster captures the Mediterranean drought signal, but also that it can be used as a semi-quantitative proxy, with verification results similar to the standards required in dendroclimatology (Fritts et al., 1990).

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 taken as continuous variables. In addition, the analysis confirmed 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 significance. However, *pro-pluviam* rogations may be especially relevant in valleys and coastal areas where there are no other climatic proxies. The exploration of historical documents from the main Cathedrals or municipal city archives, the Actas Capitulares, yielded the different types and payments of the rogation ceremonies that were performed in drought-stressed situations. In fact, it is challenging to determine whether the decrease in the number of rogations at the beginning and 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 short, the apparent low frequency of rogations in the 19th century could be explained by a combination of political instability in the main cities and the loss of religiosity and historical documents. Nevertheless, the institutional controls

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in pre-industrial society were so strict that many of its constituent parts remained unchanged for centuries, and rogation ceremonies are one such element. This can be explained by two different factors. First, rogation ceremonies are used within the framework of the Roman Church Liturgy, so changes can only be defined and ordered by the Vatican authorities. If there is a will to change criteria affecting the substance of liturgical ceremonies, all involved institutions must record considerations, petitions and decisions in official documents from official meetings, supported by public notaries. In addition, changes must be motivated from the highest institutional level (Pope) to the regional authorities (Bishops) and local institutions (Chapters, parishes...). This system was too complex to favor changes. A second mechanism guarantees the stability of the rogation system: if any minor or important change in rogations was instigated at local level by the population or local institutions, this interference directly affected the Roman Church Liturgy. However, it was a change not to be taken lightly as the Inquisition Court would start judicial proceedings, and could bring a criminal charge of heresy. The punishment was so hard that neither institutions nor the people were interested in introducing changes in rogations.

Further limitations when dealing with historical documents as a climatic proxy are related to 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 followed the methodology proposed in the Millennium Project (European Commission, IP 017008) and also applied in Domínguez-Castro et al., (2012). According to such proceedings and considering both the occurrence or otherwise of rogation ceremonies and the intensity of the religious acts, the information contained in historical documents can be transformed into a semi-quantitative time series (including continuous values from 0 to 3). To that extent, the ECDF analysis helped in understanding the nature of the historical documents when transformed into semi-quantitative data, confirming that they can be treated as a continuous variable. We then aggregated the annual values to develop a continuous semi-quantitative drought index (DI) where values can range from zero (absence of drought) to a maximum of 3 (severe drought). This set of procedures technically solves the structural problem of the data. However, we have added 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. Yet, we can infer with much confidence that if there was a drought of level 2 is because those types of ceremonies of level 1 did not work, and therefore the drought was still an issue for the development of the crops i.e., there is a progressive drying, but it does not have to be twice as intense. Hence, this must be taken into account when interpreting the indices.

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Moreover, 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 the extent to which patterns reflect elements of the climatic cycle or may be

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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 is further apart 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 chronologies share an observational period with the climatic data allowing the calibration/ verification approach (Fritts et al., 1990).

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In general, 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 semi-quantitative at best) does not facilitate the calibration/ verification approach in the few cases in which this control is feasible.

Despite these limitations, when our results are 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 that there was a persistent situation of atmospheric blocking and high-pressure conditions at the time.

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In the Ebro Valley and the Mediterranean area, rogation ceremonies were significantly less frequent in the year of volcanic eruptions and for the following year. 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 non-volcanic 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.

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Furthermore, a significant increase in the intensity of the droughts was observed two years after the Tambora eruption in the three clusters (Fig. 8) in agreement with findings by Trigo et al., 2009. This result is similar to that of a previous study using rogation ceremonies in the Iberian Peninsula, although it was based on individual and not regional drought indices (Dominguez-Castro et al., 2010). In addition, the normal conditions in the year of the Tambora eruption and the following year, and the increased drought intensity two years after the event, are in agreement with recent findings on hydroclimatic responses after volcanic eruptions (Fischer et al., 2007; Wegmann et al., 2014; Rao et al., 2017; Gao and Gao 2017), although 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 north-east 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.

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5. 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 semi-quantitative continuous data to develop drought indices (DIs). We regionalized them by creating three DIs (Ebro Valley, Mediterranean and Mountain) covering 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.

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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 north-eastern Mediterranean Iberian Peninsula is clearly supported by our study. This is crucial, considering that most of the high-resolution climatic reconstructions 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-Liñán et al., 2012) and the Iberian Range (Esper et al., 2015, Tejedor et al., 2016, 2017a, 2017b, 2017c), to deduce the climate of mountainous areas. iii) Particularly in the Mediterranean and in the Ebro Valley areas, significant imprints of volcanic eruptions are found 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.

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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 historical data from rogations 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), in order to accurately contextualize 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 to adapt to future scenarios, especially because climate variability is predicted to increase in the same regions where it has historically explained most of the variability in crop yields.

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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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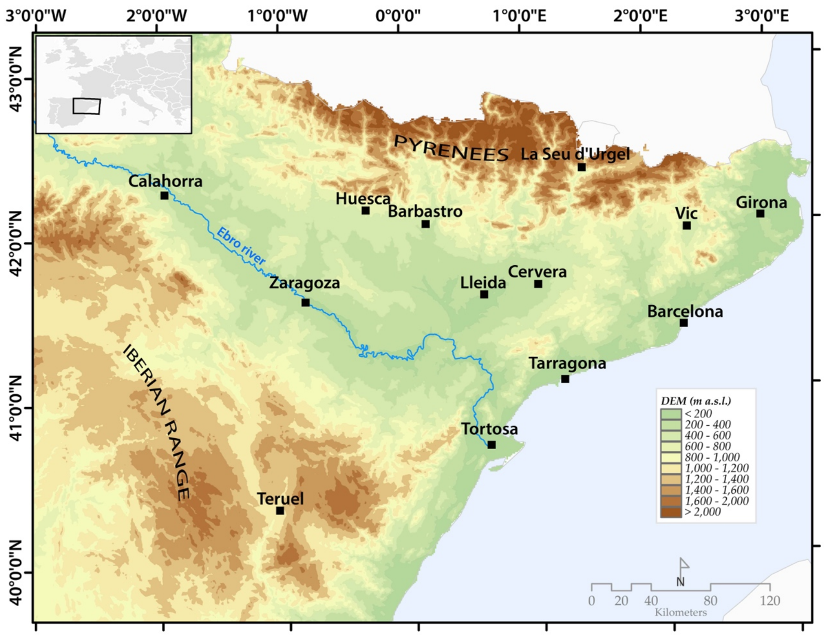

Figure 1. Location of the historical documents in the northeast of Spain.

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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.

Teruel

• Chapter Acts of the Holy Church and Cathedral of Teruel, 1604-1928, 28 vols.

Barbastro

• Cathedral Archive of Barbastro 'Libro de Gestis', Barbastro (Huesca), 1598-1925, 23 vols.

Barcelona

• City Council Historical Archive of Barcelona (AHMB), "Manual de Novells Ardits" o "Dietari de l'Antic Consell Barceloní", 49 vols., 1390-1839.

• City Council Historical Archive of Barcelona (AHMB),"Acords", 146 vols., 1714-1839.

• City Council Administrative Archive of Barcelona (AACB), "Actes del Ple", 100 vols., 1840-1900.

• Chapter Acts of the Cathedral Historical Archive of Barcelona (ACCB), "Exemplaria", 6 vols., 1536-1814.

• More than 20 private and institutional dietaries.

Calahorra

• Chapter Acts of the Cathedral Historical Archive of Calahorra (La Rioja), 1451-1913, 35 vols.

• Archives of Convento de Santo Domingo 1782–1797. First volume. 158 pages.

Cervera

• Regional Historical Archive of Cervera (AHCC), Comunitat de preveres, "Consells", 12 vols., 1460-1899.

• Regional Historical Archive of Cervera (AHCC), "Llibre Verd del Racional", 1 vol., 1448-1637.

• Regional Historical Archive of Cervera (AHCC), "Llibres de Consells", 212 vols., 1500-1850.

Gerona

• City Council Historical Archive of Girona (AHMG), "Manuals d'Acords", 409 vols., 1421-1850.

Huesca

• Chapter Acts of the Cathedral Historical Archive of Huesca, 1557-1860, 15 vols.

La Seu d'Urgell

• City Council Historical Archive of La Seu d'Urgell (AHMSU), "Llibres de consells i resolucions", 47 vols., 1434-1936.

Lleida

• National Library of Madrid (BNM), Manuscript 18496, "Llibre de Notes Assenyalades de la Ciutat de Lleida", 1 vol.

• Chapter Acts of the Cathedral Historical Archive of Lleida (ACL), "Actes Capitulars", 109 vols., 1445-1923.

Tarragona

• City Council Historical Archive of Tarragona (AHMT), "Llibres d'Acords", 92 vols., 1800 1874.

• Departmental Historical Archive of Tarragona (AHPT), "Liber Consiliorum", 286 vols., 1358-1799.

• Regional Historical Archive of Reus (AHCR), "Actes Municipals", 10 vols., 1493-1618.

• Regional Historical Archive of Reus (AHCR), Comunitat de Preveres de Sant Pere, "Llibre de resolucions", 2 vols., 1450-1617.

Tortosa

• City Council Historical Archive of Tortosa (AHMTO), "Llibres de provisions i acords municipals", 119 vols., 1348-1855.

• Chapter Acts of the Cathedral Historical Archive of Tortosa (ACCTO), "Actes Capitulars", 217 vols., 1566-1853.

Vic

• Chapter Acts of the Cathedral Historical Archive of Vic (AEV, ACCV), "Liber porterii", 10 vols., 1392-1585.

• Chapter Acts of the Cathedral Historical Archive of Vic (AEV, ACCV), "Secretariae Liber", 30 vols., 1586-1909.

• City Council Historical Archive of Vic (AHMV), "Indice de los Acuerdos de la Ciudad de Vich des del año 1424", 2 vols., 1424-1833.

• City Council Historical Archive of Vic (AHMV), "Llibre d'Acords", 49 vols., 1424-1837.

Zaragoza

• Chapter Acts of the Cathedral Historical Archive 'Libro de Actas del Archivo de la Basílica del Pilar', 1516–1668, 17 vols. 2.600 pages.

• City Council Historical Archive of Zaragoza, 1439–1999. 1308 vols. 35.000 pages.

• City Council Historical Archive of Zaragoza. 'Libro de Actas del Archivo Metropolitano de La Seo de Zaragoza', 1475–1945. 81 vols. 12.150 pages.

Table 2. Documentary references for administrative public documentary sources used for rogation monthly indices (all documents are generated and initialed by public notaries). Noted that only the official documents are shown. Each documentary record is given reliability load with the public notary rubric that acts like secretary. This procedure is currently still in force for the same type of document, which is still generated at present time.

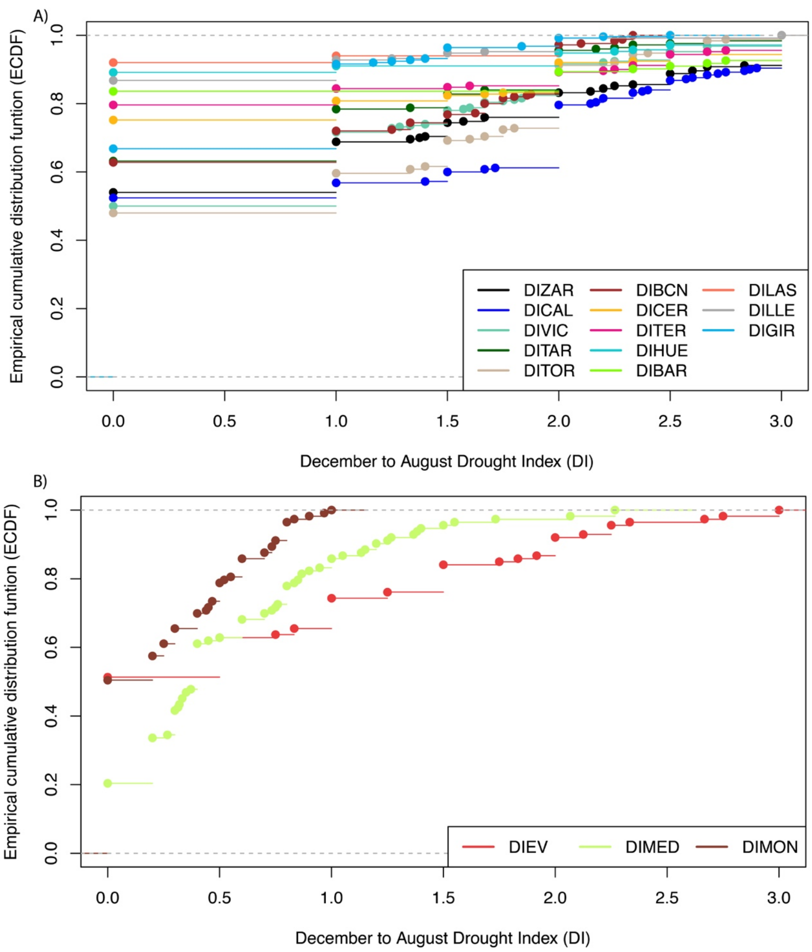

Figure 2. The empirical cumulative distribution function (ECDF), used to describe a sample of observations of a given variable. Its value at a given point is equal to the proportion of observations from the sample that are less than or equal to that point. ECDF performed for the local drought indices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

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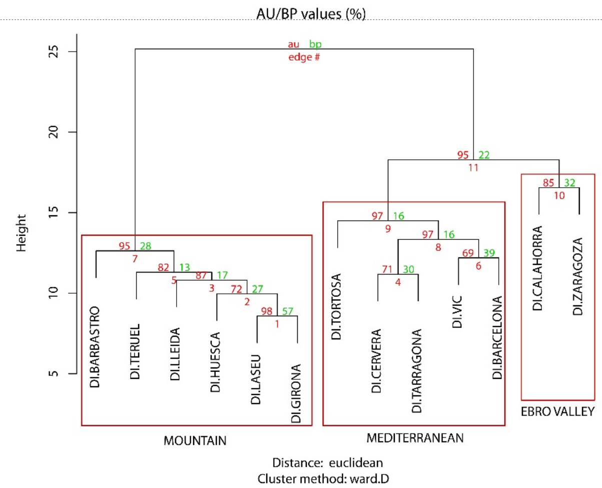

Figure 3. Dendrogram showing the hierarchical cluster analysis of the drought indices developed from the historical documents for each location. The AU (approximately unbiased *p-value*) is indicated in red and the BP (bootstrap probability) is presented in green.

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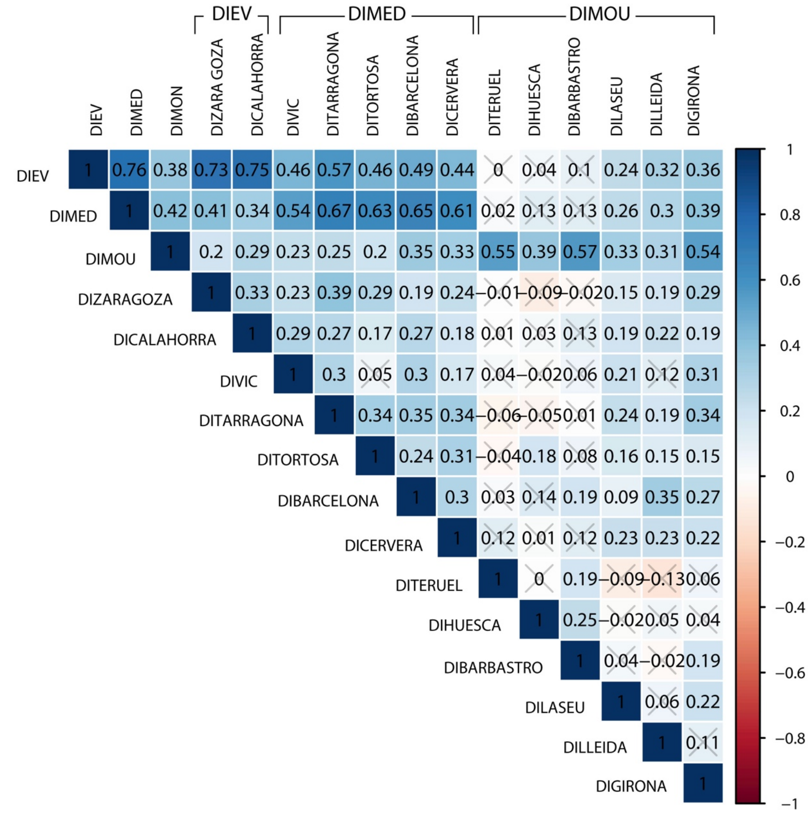
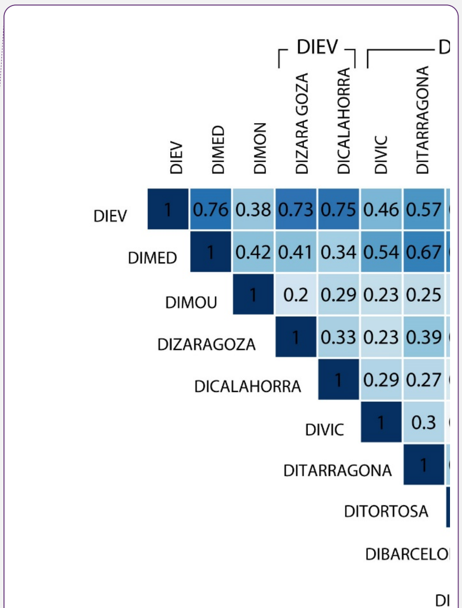


Figure 4. Correlation matrix (Spearman) between the individual drought indices and the cluster drought indices for the period of 1650-1899. Values are significant at $p<0.05$, except those marked with a gray cross, which are not significant.



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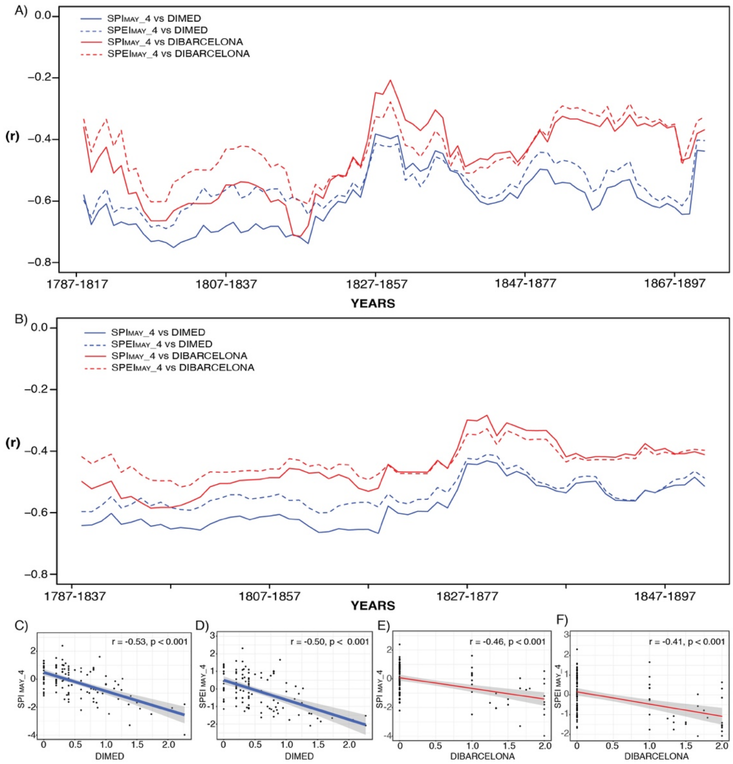

Figure 5. A) 30y moving correlation between DIMED, DIBARCELONA and the instrumental computed SPI and SPEI. B) Same but 50y moving correlations. C) Correlation (Spearman) between DIMED and SPI_{MAY}_4 for the full period (1787-1899). D) Correlation between DIMED and $SPEI_{MAY}$_4 for the full period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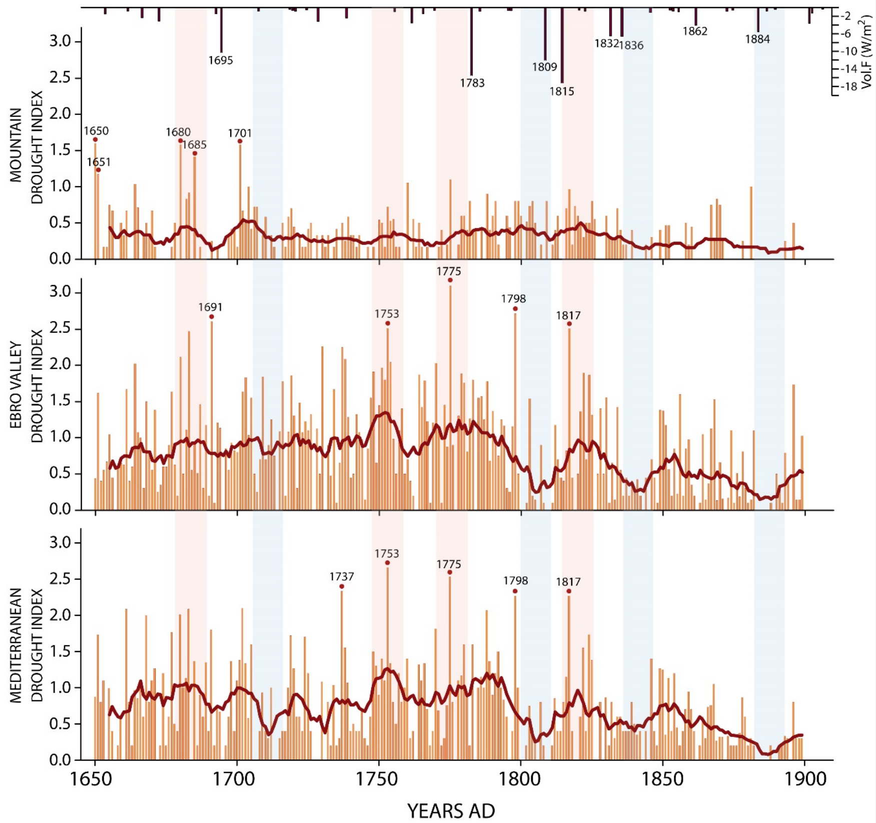

Figure 6. Drought indices of the three clusters, DIMOU (Mountain), DIEV (Ebro Valley) and DIMED (Mediterranean). Vertical orange bars represent the drought index magnitude, 0 denotes normal conditions, and 3 denotes an extreme drought year. The extreme drought index years are also highlighted with a 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.

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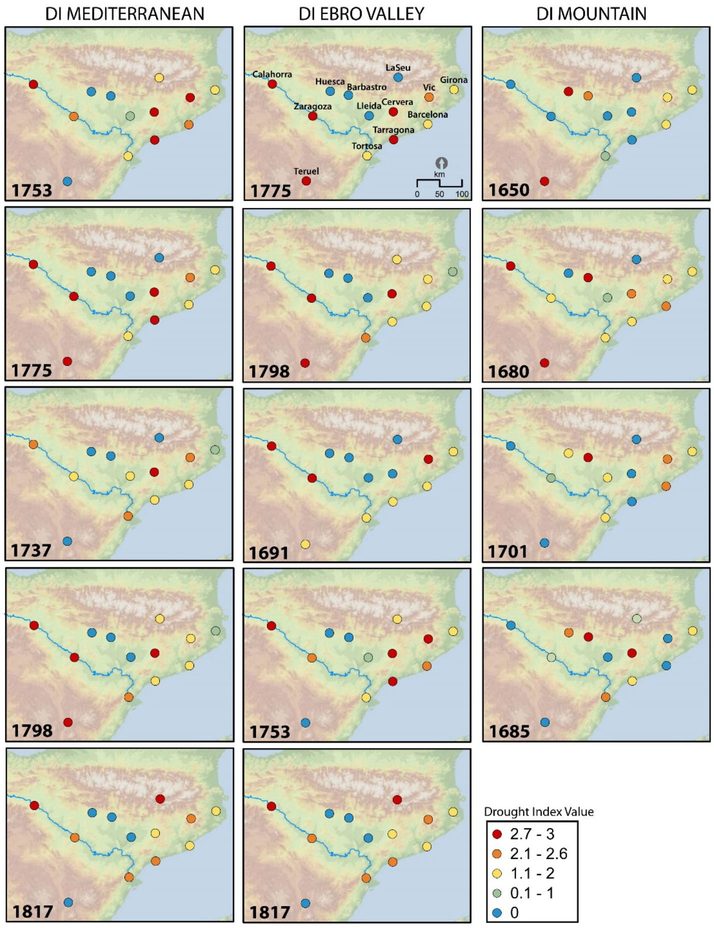

Figure 7. Spatial distribution of the most extreme drought years (based on the 99th percentile of the cluster drought indices). The distribution is ordered top-down. The drought index value (magnitude) for each site within the cluster is also represented. The legend of the drought index value is based on the 30th, 60th, 70th and 90th percentiles.

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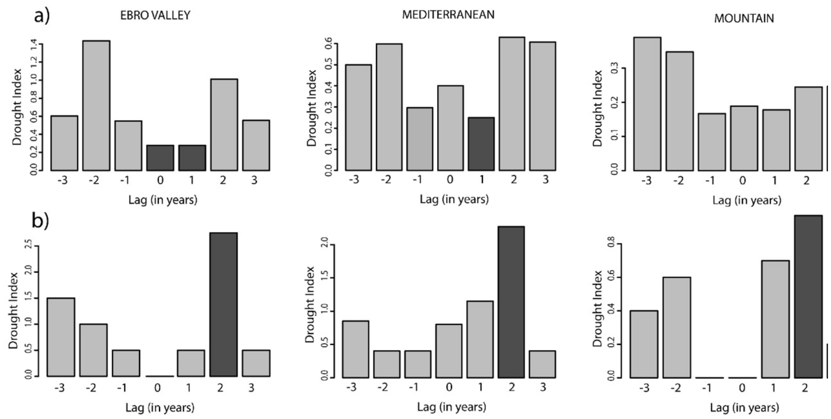

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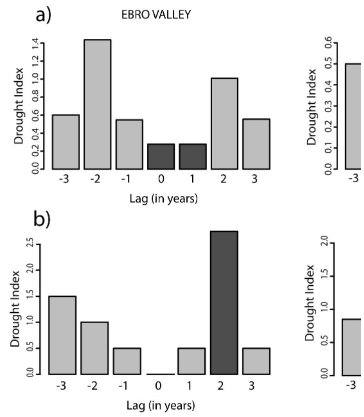

Figure 8. a) Superposed epoch analysis (SEA) of the three regional drought indices, DIMOU (Mountain), DIEV (Ebro Valley) and DIMED (Mediterranean), with major volcanic events from Sigl et al., 2015. Black shadows show significance at *p*<0.01, i.e., significantly lower or higher drought index values after the volcanic event. b) SEA of only the Tambora (1815) event showing a significant (*p*<0.01) increase in the drought index.

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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 3. Rogation levels according to the type of ceremony celebrated.

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