Reconstruction of drought episodes for central Spain from rogation ceremonies recorded at the Toledo Cathedral from 1506 to 1900: A methodological approach

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A B S T R A C T

Rogation (ceremonies to ask God for rain: pro-pluvia, or to stop raining: pro-serenitate) analysis is an effective method to derive information about climate extremes from documentary data. Weighted annual sum by levels has been a widespread technique to analyze such data but this analysis is liable to be biased to spring values as these ceremonies are strongly related to farming activities. The analysis of the length of pro-pluvia periods (the time span during which rogations are carried out in relation to a drought event) and the combination of annual and seasonal information offers a more objective criterion for the analysis of the drought periods and an increase in the resolution of the study.

Analysis by the pro-pluvia periods method of the rogation series from the Toledo (central Spain) Cathedral Chapter allows a good characterization of the droughts during the 1506–1900 period. Two drought maxima appear during the 1600–1675 and 1711–1775 periods, characterized by rogations during almost all the year, with a middle stage (1676–1710) when droughts were less frequent and their length shortened.

Sea level pressure patterns for the instrumental and documentary periods show that droughts were mostly related to a north-eastern position of the Azores High that displaced the Atlantic low pressure systems towards a northern position. There is a weak relation with the North Atlantic Oscillation but this fact is related to the local character of the series that increases the weight of the local factors.

Comparison of rainfall/drought records around Spain and the Western Mediterranean reveals the heterogeneity of their distribution in time and space as well as stresses the need of more and longer reconstructions. Better knowledge of drought variability would help to improve regional models of climate extremes and the understanding of the atmospheric patterns related to their development.

1. Introduction

Drought is one of the climate extremes with greatest incidence in human development. Water is needed for human life for drinking and to obtain food, as natural or artificial irrigation is needed for agriculture and also for the cattle. Relevance of drought in human activity is testified by migratory movements from dry regions to wetter areas and by decline of civilizations and empires as consequence of prolonged water deficit (Weiss et al., 1993; Cullen et al., 2000; deMenocal, 2001; Hodell et al., 2001, 2007; Haug et al., 2003; Nicoll, 2004; Drysdale et al., 2006). But it is also important as an increase in climate extremes is very likely in the Mediterranean region in future scenarios (Brunetti et al., 2004; Tebaldi et al., 2006).

One of the difficulties in the research of drought is its definition (meteorological, hydrological, agricultural, socioeconomical droughts, Wilhite and Glantz, 1985), which determines its metrics and the threshold of rainfall deficit (duration of the deficit) that defines the "drought state". Depending on the key parameter chosen to define the drought event there are several indexes that can be used to quantify drought: i.e. Palmer Drought Standardized Index (PDSI, Palmer, 1965), Standardized Precipitation Index (SPI, McKee et al., 1993), "Percent of Normal", deciles (Gibbs and Maher, 1967), etc. These indexes are of variable complexity and, usually, they provide non-comparable results (Byun and Wilhite, 1999) or use assumptions weakly justified on a physical or statistical model (Alley, 1984).

But most studies of recent droughts coincide in the great variability in time and space of drought (Santos et al., 2000). This fact determines that rainfall threshold is dependent on the location of the study (Hisdal and Tallaksen, 2000).

Droughts have been mostly studied for short time scales (ranging from 50 to 150yr) based on instrumental data and they stress the need of longer time series in order to improve knowledge on the return periods

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of drought events and the changes in its spatial distribution (Santos et al., 2000).

Long drought/rainfall data sets arising from dendrochronology for the Mediterranean basin are mainly limited for a few regions: Morocco (Munaut, 1982, Till and Guiot, 1990; Chbouki et al., 1995; Glueck and Stockton, 2001; Esper et al., 2007), Turkey (Akkemik, 2000; D´Arrigo and Cullen, 2001; Touchan et al., 2003, 2005a; Akkemik and Aras, 2005; Akkemik et al., 2005; Akkemik et al., 2007), Spain (Creus et al., 1995, 1997; Saz and Creus, 1999, 2001; Saz, 2004) and East Mediterranean — Greece, Turkey, Lebanon, Syria and Cyprus (Touchan et al., 2005b). But the great variations in precipitation from one place to another makes difficult to find a homogeneous response of ring-width to precipitation, and because the long-lived trees, useful for this research, grow in areas where precipitation is not a limiting factor (Martinelli, 2004).

To extend the spatial coverage of these series one of the more valuable proxies are documentary data as they provide descriptions of weather and their time resolution can reach up to daily scale.

During recent decades, historical climatology has been increasingly contributing to analyze the climate variability of the last millennium (Brázdil et al., 2005; Luterbacher et al., 2006). One of the methods contributing to such advance has been the analysis of rogation ceremonies to estimate rainfall or drought series.

These ceremonies are a typical ritual of the Roman Catholic Church that was used in all the Spanish Empire to sight for the end of the Divine punishment of drought periods (pro-pluvia rogations) or long wet/stormy spells (pro-serenitate rogations).

Their potential as a climate proxy was recognized by Giralt (1958) and due to their wide time range and their systematic record in the archives of a considerable number of localities of the "Catholic world" (Barriendos, 2005) they have been frequently used (Álvarez Vázquez, 1986; Martín-Vide and Barriendos, 1995; Barriendos, 1997, 2005; Piervitali and Colacino, 2001; Romero and Máyer, 2002; Zamora Pastor, 2002; Vicente-Serrano and Cuadrat, 2007; Rodrigo and Barriendos, this volume).

Methods to quantify these data vary from the simple counting of the number of ceremonies by year or trying to find the relation between the

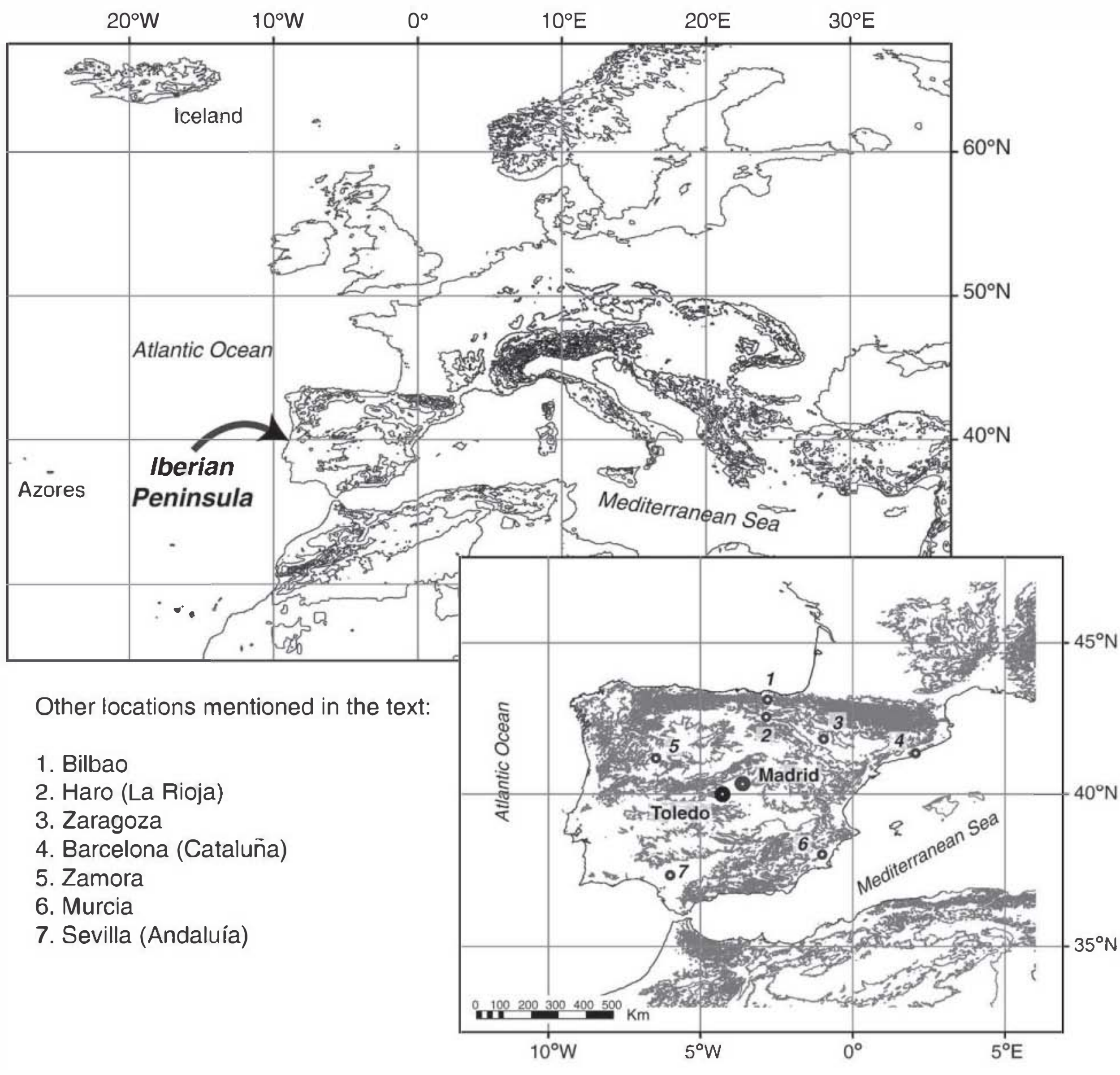

Fig. 1. Location of the studied area.

economical cost of these ceremonies and the droughts (Álvarez Vázquez, 1986) to weighted sums of the ceremonies on an annual or longer time scale with discrete weights related to the liturgical acts developed in each situation (Martín-Vide and Barriendos, 1995; Barriendos, 1997, 2005; Piervitali and Colacino, 2001; Romero and Máyer, 2002; Zamora Pastor, 2002). Filtering of the results by running averages ranging from 5 yr to 31 yr (Martín-Vide and Barriendos, 1995; Barriendos, 1997, 2005; Zamora Pastor, 2002; Vicente-Serrano and Cuadrat, 2007) is a usual technique to mask the high frequency signals and to reveal the long-term trends.

This paper focuses on the analysis of rogations by using the duration of periods defined by a set of ceremonies close in time instead of using the usual weighted sum of ceremonies in order to obtain an estimate of the length of the drought periods. The application of this methodology to the rogation series from the Toledo Cathedral (central Spain) will serve to characterize the 1506–1900 AD period in inland Spain.

2. Location

Toledo is located in the Southern Spanish Meseta (39°51′N, 4°01′W) at 540 m above sea level (Fig. 1). It is protected from the marine influence by the Central System and Sierra Morena. From the 6th century AD until 1563 AD it was the Spanish capital, but it's still an important administrative and religious centre (archiepiscopate).

Present day climate is temperate Mediterranean–continental with 357 mm of average annual rainfall, a dry period in summer, cold winters (average: 7.3 °C), warm summers (average: 24.6 °C) and a wide annual range of temperature (from −10 °C in winter to up to 40 °C in summer).

3. Source of data and methods

3.1. Data

Rogation data come from the 1) Toledo Cathedral Chapter Acts, 121 volumes that record the daily life from 1466 to 1599 AD, 2) "Casos subcedidos en diversos tiempos en la Sta. Iglesia de Toledo desde el año 1435 sacados de los libros capitulares de ella" a book started by Juan Bautista de Chaves Arcayos who resumed the cathedral chapter records from 1434 to 1599 AD and incorporated his own news and was later followed by other chapter members until the middle 18th century AD, 3) Chapter Books (1464–1914), 331 volumes used to fill gaps in the Chapter Acts. Those books were studied at the Toledo Cathedral Archives and at the Toledo Townhall Archives.

The collected rogation series covers from 1506 to 1900 and it is composed by 341 pro-pluvia rogations, 36 pro-serenitate rogations and 94 thanksgiving masses (ceremony to celebrate the end of the weather phenomena that led to a rogation). Most of these rogations correspond to spring ceremonies (Fig. 2a) and distribution of levels in time is not homogeneous (i.e. Level III ceremonies are more frequent during the 16th century, Fig. 2b).

As Rodrigo and Barriendos (this volume) point, there is no overlapping period with the instrumental series of Toledo (covering the 1909–2002 period). But comparison of Toledo series (Buenavista and Lorenzana stations) to the instrumental record of Madrid (Retiro station) reveals a good correlation of their rainfall series both in number of rainy days (Fig. 3a), amount of rainfall (Domínguez-Castro, 2004) and the derived Standard Precipitation Index (Fig. 3b). As a consequence, Madrid rainfall series were chosen as reference series in this paper.

The annual correlation coefficient for the days of rain of the two stations is the 0.894 and Fig. 3a shows the similarity on the distribution of the days of rain per month at Toledo and Madrid. Table 1 shows that Madrid is slightly rainier than Toledo, but the correlation coefficient for both cities is high for all seasons and the Coincidence Index (Domínguez-Castro, 2004) supports the similarity of both series

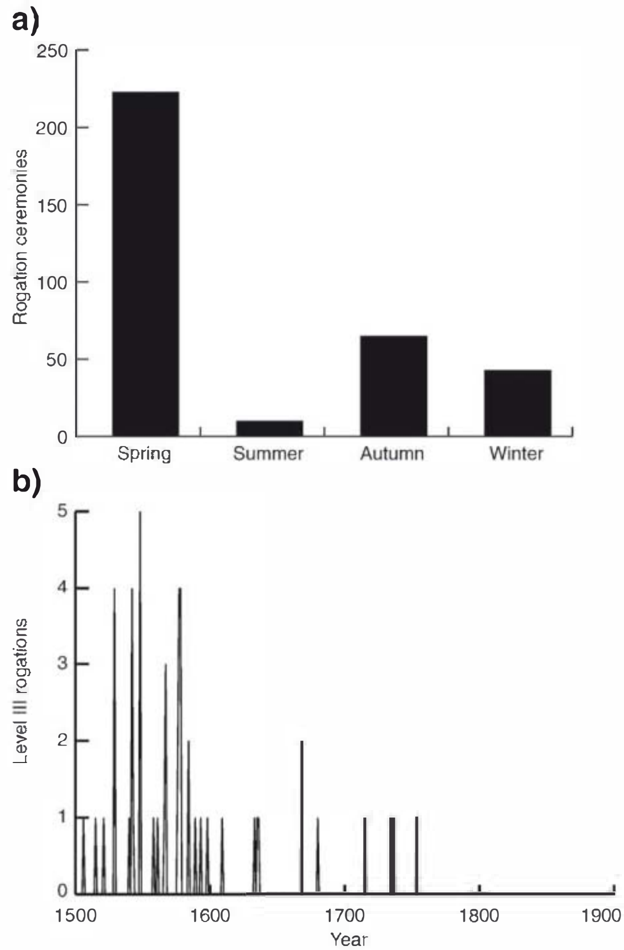

Fig. 2. a) Seasonal distribution of pro-pluvia rogations (1506–1900) and b) distribution of Level III rogations in Toledo series.

(Table 1). This index (CI) gives an idea of the similarity of the series at daily scale and it is calculated as:

$$CI = (CD{-}DMC)/(TD{-}DMC) \quad (1)$$

where CD (coincidence of days) is the number of rainy or dry days that coincide in both cities, TD (total days) is the length of the studied time window, in our case one season, and DMC (days of mandatory coincidence) is the number of rainy or dry days that mathematically must coincide (i.e., if Madrid series is composed by 60 days of rain and 40 dry days and Toledo series shows 30 rainy days and 70 dry days, there are 10 dry days that must coincide, then DMC = 10).

Madrid series has been constructed with the data provided by the Meteorological National Institute of Spain filling some gaps with the GHCN series (Peterson and Vose, 1997) covering the 1850–2002 period and imputing missing values with the Enhanced-Maximisation (EM) and Data-Augmentation (DA) algorithms (Schafer, 1997). Further extension of the series has been achieved by means of a generalized lineal model of the number of rainy days by month (obtained from daily reports of the Royal Academy of Medicine) to the monthly rainfall extending the series down to 1786 (with some gaps).

The Standardized Precipitation Index (SPI), both for Toledo and Madrid, has been elaborated following Lloyd-Hughes and Saunders (2002) but using the Pearson III distribution as proposed by Vicente-Serrano (2006). This index was selected by its properties: only depends on rainfall data, provides information on duration, magnitude and intensity of droughts (Hayes et al., 1999) and it can be calculated for several time scales allowing to identify various types of

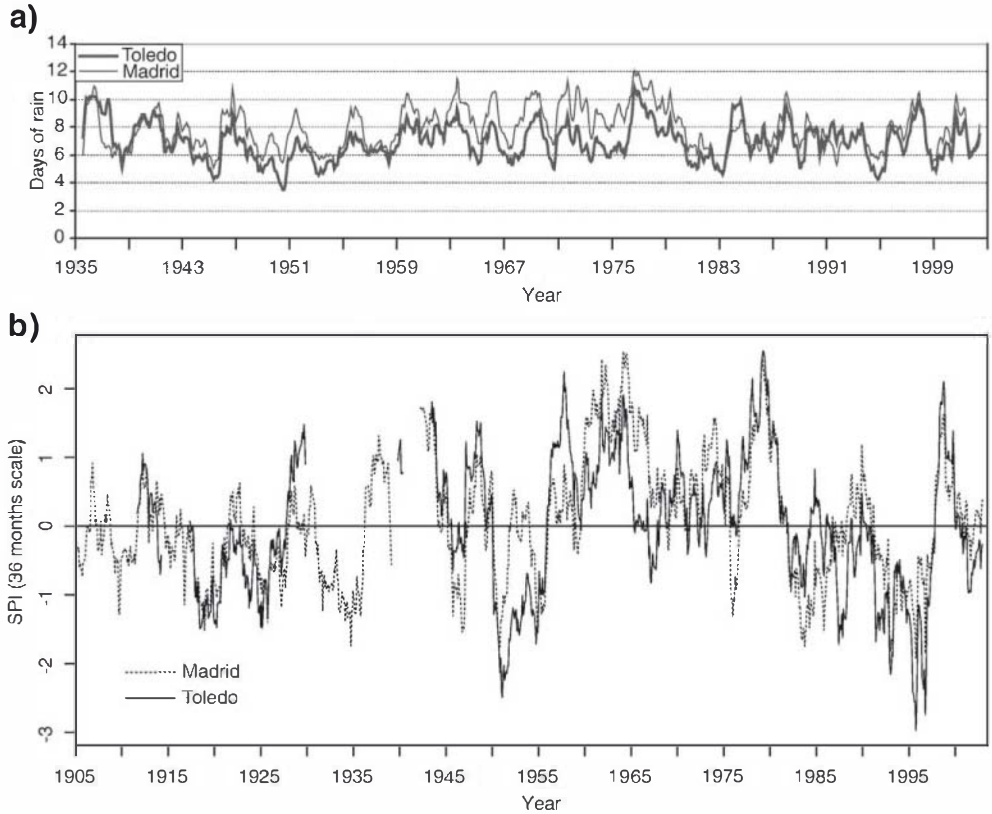

Fig. 3. a) 12-month running average of rainy days by month for Madrid (thin line) and Toledo (thick line) for the 1935–2002 period. b) SPI at 36 months scale for Madrid and Toledo from 1905 to 2002.

drought (agricultural, meteorological, hydrological or environmental) (Vicente-Serrano, 2006).

3.2. Methodology

In order to characterize the drought periods, this paper just focuses in the pro-pluvia rogations.

Our main methodological goal is to develop an estimate of drought duration based on the length of the periods between ceremonies, as an alternative to the use of the levels of the ceremonies as discrete weights.

3.2.1. Estimates of drought length

Common weighting of rogations is based on a hierarchy of liturgical rituals that rose in importance as the severity of the drought increased. But that rank of ceremonies changed among localities both in number and manifestations giving place to different scales (Table 2).

Changes with time in the preferences of the city council or religious authorities can also mask the real severity of a drought. As an example, Level III processions are concentrated during the 16th century (Fig. 2b), but the “abundant” grain production during this century, in comparison to the 17th century production (Fig. 4), points to a not so unfavourable climate conditions.

In consequence, weighting of rogation by levels provides an inhomogeneous measure of drought, as its meaning varies in time and space, difficult to apply for the comparison among periods and localities.

But, independently of their level, these ceremonies use to be grouped in time defining a “pro-pluvia period” (PP) that spans from the date of a first ceremony that can be followed by successive rogations separated in time less than 20 days (a time threshold between periods), to the date of an ending thanksgiving mass or rogation. A special but not so infrequent case is a PP defined by a single rogation ceremony. The PP can overlap with the rainy period following the drought and, therefore, it doesn't provide a precise date of the end of the dry conditions but of the water deficit, which is the criteria for drought definition. So, the PP represents the amount of time that a community was continuously praying for the end of drought, what means an amount of rain enough to alleviate the water deficit.

Therefore, total length of the drought period is equal to the sum of the lengths of the PP and the previous dry period (PDP) that predates

Table 1
Seasonal average of rainy days (1935–2002) for Madrid and Toledo

	Madrid			Toledo				
	Rainy days	Precipitation (mm)	Standard deviation (mm)	Rainy days	Precipitation (mm)	Standard deviation (mm)	Correlation coefficient*	Coincidence Index
Winter	33.94	133.3	71.0	29.95	106.9	58.0	0.90	0.76
Spring	34.50	131.0	52.3	30.86	115.5	52.5	0.81	0.75
Summer	17.53	50.4	29.3	14.42	46.2	30.3	0.82	0.64
Autumn	26.08	137.8	72.3	22.33	105.1	48.0	0.82	0.73

*: $p<0.01$.

Table 2
Drought severity levels accordingly to the liturgical rituals of different cities

	Barriendos (1997, work in progress)				Romero and Máyer (2002)	Zamora Pastor, (2002)
	Sevilla	Murcia	Toledo	Barcelona	Gran Canaria	Orihuela
Level I	Collecta pro pluvia and intra ecclesiam prayers with exhibition of the Blessed Sacrament.	Joy Masses, Collecta pro pluvia.	Masses with Collecta pro pluvia and chants.	Simple rogations, novenarios and Collecta pro pluvia.	"Water Mass", penitences and prayers.	Public rogations
Level II	Intra ecclesiam liturgical acts with images.	Exhibition in the Cathedral of Madonnas or Lignum Crucis.	Novenarios with exhibition of images and procession inside the Cathedral.	Exhibition of relics in the Cathedral Main Altar.	Processions with the city saints.	Masses with Collecta pro pluvia.
Level III	Extra ecclesiam liturgical acts with images.	Processions to sanctuaries with images or relics.	Processions with images or relics inside the city.	Procession along the main streets with relics.	General processions with the city and town saints and the Island patron.	Exhibition of the intercessor
Level IV	Procession around the city with the image of the Holy Christ.	General blessing of the fields.	Processions with images or relics around the city reaching the city walls.	Immersion in the harbour of the Lignum Crucis. Exhibition of the Blessed Sacrament, masses. General blessing of fields.		Procession of the intercessor.
Level V	Processions to sanctuaries with relics, Lignum Crucis or inside the Cathedral with images.			Pilgrimages.		

the PP. Pro-pluvia period length can be calculated from the dates of the rogations but, without any other information, it is impossible to know the length of the previous dry period.

Fig. 5a shows the drought length (DL) and the PDP and PP values for years with both daily instrumental (number of rainy days or amount of rain) and rogation records for the 1817–1900 period. One of the most relevant facts is that the PDP (the dry period which triggers the rogation mechanism) oscillates around 44.2 days with a standard deviation of 7.7 days and no data goes beyond $\pm 2\sigma$. Such low variability implies that it is possible to obtain a statistically meaningful estimate of DL from the PP values without knowledge of the PDP (Fig. 5b). It is worth to note the similarity between the intercept of the lineal model (45.55) and the mean of the PDP, what means that this term is captured by the model.

Further support for this relation is provided by the comparison of the length of the pro-pluvia period by season to the seasonal SPI for the 1850–1900 period (in order to use direct measurements of amount of rainfall) that allows to establish a lineal relation between the magnitude of both indexes ($r = -0.44$, $p < 0.01$). The correlation of both indexes is lower than in the case of the relation between DL and PP. This can be attributed to the fact that rogations are triggered by a rainfall deficit below a certain threshold, but once surpassed that threshold the rogation phenomena is mostly controlled by the DL and it shows low sensitivity to the variations in the amount of rain while the SPI is sensitive both to the DL and to the amount of rainfall. Coincidence in time of rogations with negative SPI values (dry periods) is presented in Fig. 5d. This figure is also important as it makes clear that while rogations are coincident with drought events, not all drought events are accompanied by a rogation. Thus, rogations are evidence of drought events but they are not a continuous record of drought and this must be taken into account when using these ceremonies to reconstruct drought records.

These results, besides the fact that the number of rogations is lower than the average due to political factors during the last half of the 19th century, suggest that the length of the pro-pluvia period can be used as a proxy of the total length of the drought with a not so large uncertainty.

Single rogations, those located beyond 20 days of other rogation or thanksgiving mass, have no pro-pluvia period length by themselves and they have been assigned a length of 1 day.

3.2.2. Seasonal vs. annual scale

Several researchers have highlighted the benefit of the seasonal vs. annual resolution in historical climate analysis (Le Roy Ladurie, 1983; Xoplaki et al., 2001, 2005; Luterbacher et al., 2004, 2006; Brázdil et al., 2005; Frank and Esper, 2005; Casty et al., 2005; Pauling et al., 2006; Büntgen et al., 2006; Raible et al., 2006). This is evident in the Mediterranean region, characterized by the contrast among seasons. But in the case of the analysis of rogations, this fact is emphasized by the strong link between rogations and farming activities, which concentrate their water demand in certain periods of the year. This is demonstrated by the documents concerning the rogations: "... being so necessary water, both for the fields, as it is impossible neither to sow nor to sustain the animals, and for the health..." (Toledo

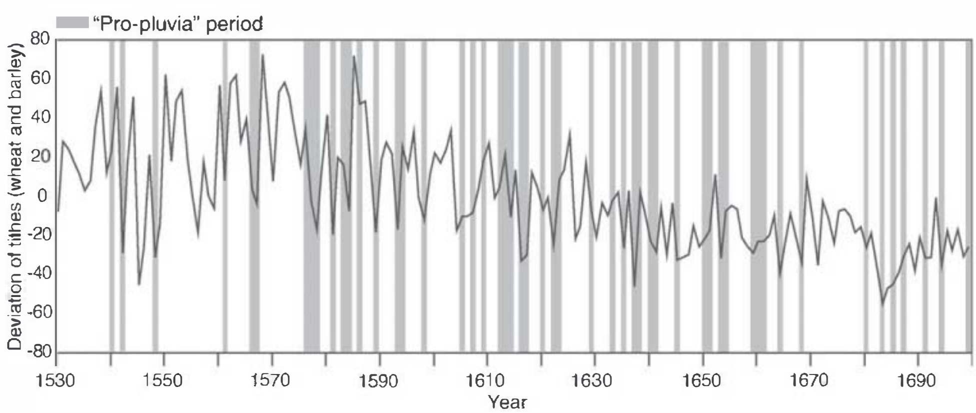

Fig. 4. Average of wheat and barley tithes for the Illescas, Escalona, Ocaña and Montalban archpriesthoods (López Salazar and Martin Galán 1981) (line) and pro-pluvia rogations (bars) distribution for the 1530–1699 period.

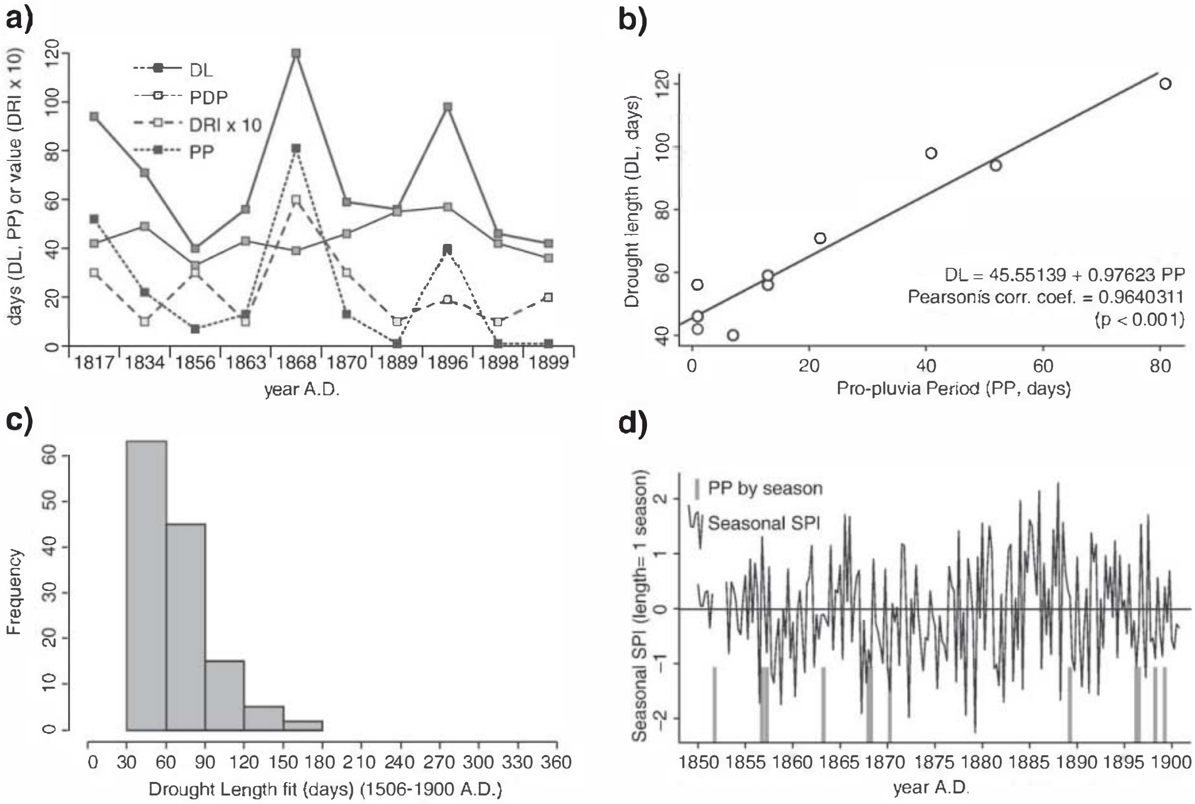

Fig. 5. a) Comparison among the drought length (DL), previous dry period (PDP), Drought Rogation Index multiplied by 10 (DRI × 10) and pro-pluvia period (PP), b) lineal regression between the DL and the PP index, c) frequency histogram for DL obtained from previous fit, and d) seasonal SPI from Madrid (line) and pro-pluvia period index (bars) for the period 1850–1900.

Cathedral Chapter Acts, vol. 56, sheet 21, rogation on 15th of November of 1726). Fig. 4 presents the relation between wheat and barley tithes (López Salazar and Martin Galán, 1981), a grain production proxy, and rogations. Despite the possible influence of social, economical or technological factors in some of the events or trends, the near constant coincidence between years of scarce grain production and rogations supports the relation between farming activity and rogations.

The seasonality on water demand from farming activities conditions the interpretation and quantification of drought periods as the threshold to trigger a rogation was not the same in spring (growth of crops) or autumn (preparation of sowing, growth of pastures) as in summer (which was assumed to be dry and a rogation will be triggered by an exceptional drought). Consequently, rogations are shifted towards those seasons (Fig. 2a) causing a bias of the annual estimations.

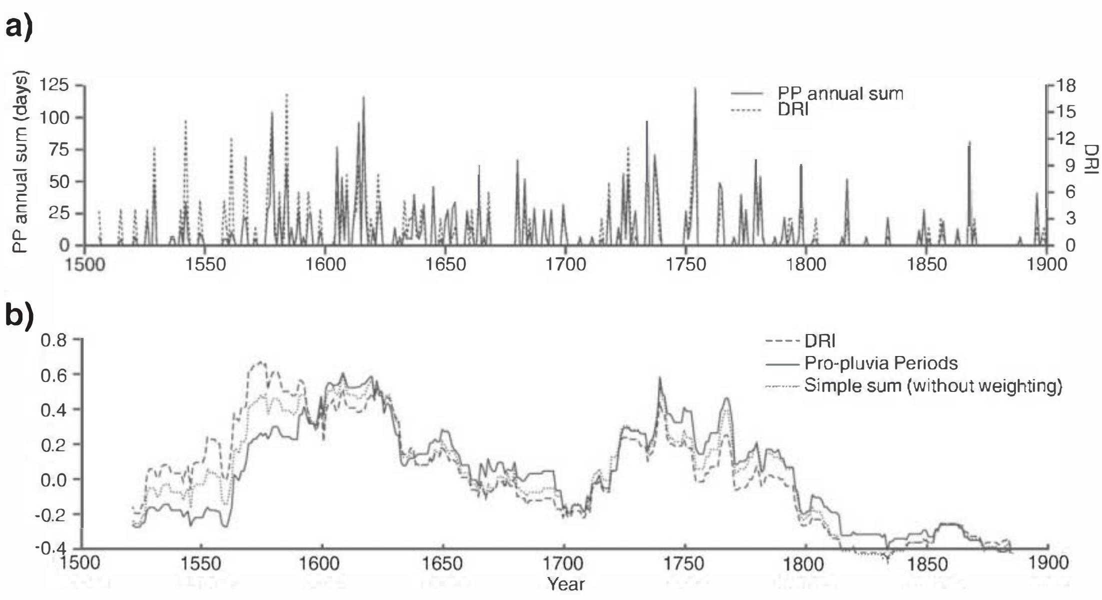

Fig. 6. a) Annual sum of the pro-pluvia periods (values of 1 have been assigned a value of 5 for graphical purposes) and Drought Rogation Index (DRI). b) 31-year running average of the standardized DRI (dashed), standardized PP method (continuous) and standardized non-weighted sum of rogations (dotted).

The distribution of the drought length obtained by fitting the lineal model of Fig. 5b for the 1506–1900 A.D. period shows that most rogations represent events shorter than a season and no rogation represents droughts that exceed two seasons (Fig. 5c). Consequently, single rogations provide information about annual and seasonal droughts but not about longer periods. This is also evidenced in Fig. 5d as rogations coincide with dry periods marked by the SPI but their distribution in is not denser in these periods.

3.3. Comparison between the pro-pluvia period method and the Drought Rogation Index

In order to check the gain obtained with the pro-pluvia period method, we have compared the results of this method with those obtained by the use of the Drought Rogation Index (DRI, Martín-Vide and Barriendos, 1995) for the years with both available rogations and historical–instrumental data (Fig. 5a).

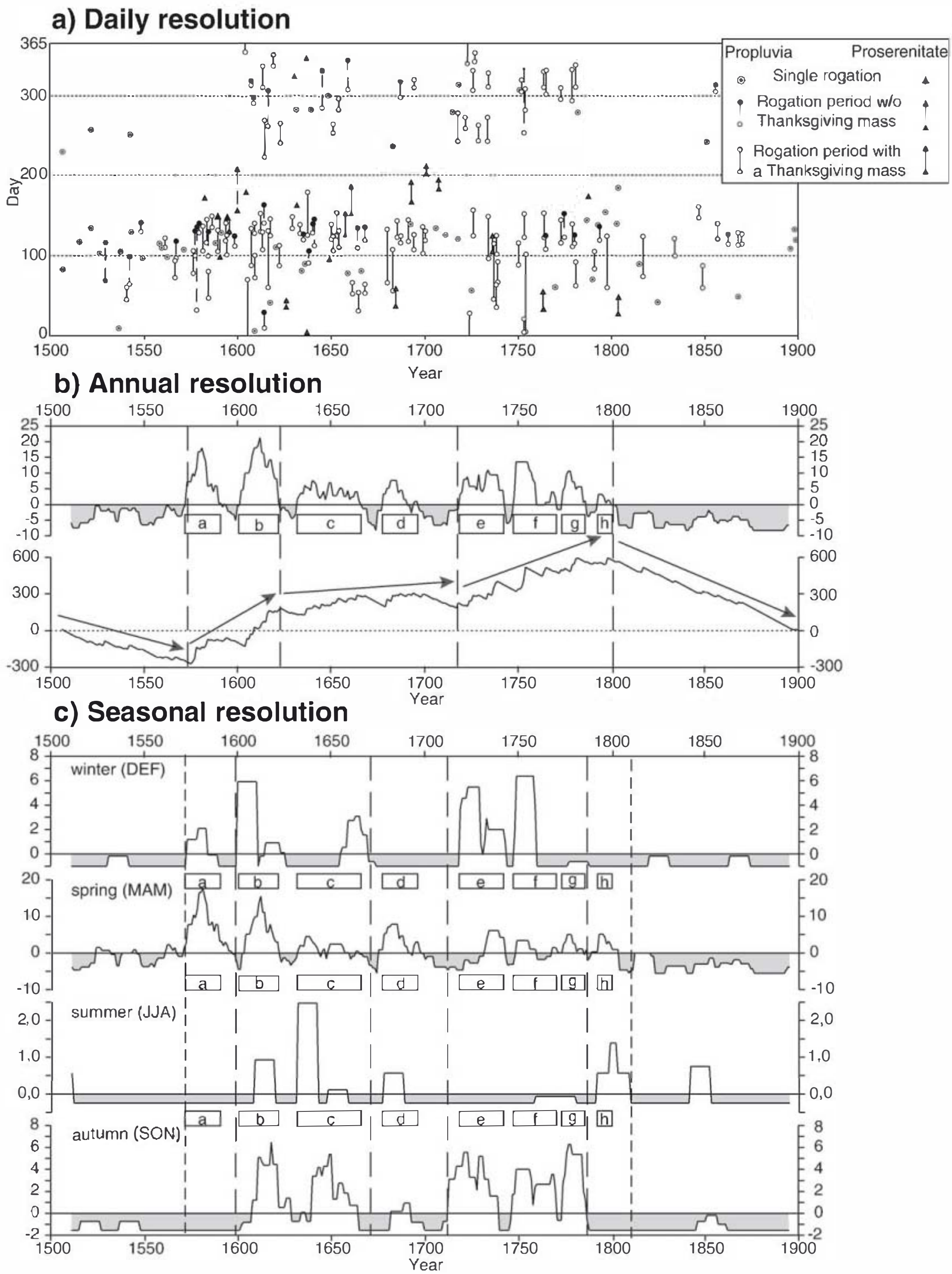

Fig. 7. a) Daily distribution of the rogation series of the Toledo Cathedral Chapter for the 1506–1900 period. Circles: pro-pluvia rogations, triangles: pro-serenitate rogations, continuous line: period finished by a thanksgiving mass, dashed line: periods finished by a rogation. b) Upper: 11-year running average of the difference of the length of the pro-pluvia periods in relation to the average length; lower: cumulated differences for the length of the pro-pluvia periods. c) 11-year running average of the difference in length of the pro-pluvia periods in relation to the average length on a seasonal basis.

Despite the good correlation between the DRI and the PP (0.74, p=0.014), the Pearson's correlation coefficient between PP and the DL is higher and statistically more meaningful (r=0.96, p<0.001) than the correlation between the DRI and the DL (r=0.58, p=0.076). In addition, Fig. 5a shows the good agreement in location and trends of the PP against the DL, whilst while the DRI fails to characterize some drought events as the resolution of the DRI (discrete scale) is coarser than the PP resolution (continuous scale).

The comparison of the Drought Rogation Index and the pro-pluvia period method applied on an annual scale (the DRI basis) reveals differences in the estimation of the severity of the droughts (Fig. 6a). The most evident case is the evaluation of the 16th century, with a high number of Level III rogations, and the lack of coincidence in the absolute and relative maxima (only five on twelve are coincidental in both methods).

However, the 31-year running average (following Martín-Vide and Barriendos, 1995; Barriendos, 1997) on the standardized indexes shown in Fig. 6b reveals that trends in both series are very similar besides the shift of the first maxima which is placed in the late 16th century by the DRI (dashed line) and at the first half of the 17th century by the PP method (thick line). This shift is related to the anomalous number of Level III rogations during the 16th century (Fig. 2b), what has been related in Section 3.2 to social factors during this period.

It is worth to mention that the same procedure applied on the non-weighted sum of the annual rogations (dotted line) is also coincidental with the results of both methods. This implies that the longer term trends, not masked by the 31-year running average, are less sensitive to the manipulation of data.

4. Results and discussion

4.1. Drought characterization by the pro-pluvia period method for Toledo for the 1506–1900 period

The rogation series of the Toledo Cathedral Chapter for the 1506–1900 period, applying the pro-pluvia period (PP) method, is composed by: 85 PP finished by thanksgiving masses, 25 PP not finished by thanksgiving masses, 50 single PP, 9 pro-serenitate periods finished by a thanksgiving mass, 4 pro-serenitate periods without a final thanksgiving mass and 8 single pro-serenitate rogations (Fig. 7a).

Taking into account that most of the record is composed by missing values, to analyze this series these values have been replaced by 0 and an 11-year moving average filter has been applied as the best option between the non-filtered series, too noisy, and the 31-year filter (the "climatological normals" period), which overweighs the 0 values causing shifts in the relative minima and maxima. Filtering on an annual scale of the PP reveals three main phases on the basis of their length (Fig. 7b upper):

1) 1506–1575: Droughts are scarce and their lengths are under the average during the whole phase.
2) 1576–1800: The more severe droughts develop during this phase. Values are upon the average, but short periods below average (3 to 22 yr in length each) appear with a frequency around 33 yr. This phase shows an early (1576–1624) and a late (1719–1800) stages of severe droughts detached by a middle stage (1625–1718) of less severe droughts (Fig. 7b lower).
3) 1800–1900: Scarce droughts that show the minimum values of the series and are all below the average.

Table 3
Dry periods for the Iberian Peninsula and other Mediterranean areas ("( )": dry spells in dry periods; "[ ]": dry spells in wet periods; DS: documentary sources; ID: instrumental data; TR: tree-rings, M: models; i.g.: inferred from their graphs)

Area	Authors	Dry periods	Comments
Toledo (central Spain)	This work	1576–1600, 1601–1675, 1711–1775, 1775–1810	DS, ID
Haro (N Spain)	Saz and Creus (2001)	1590–1605, 1646–1655, 1751–1759, 1768–1772,1870–1882, beginning of the 20th c., 1963–1974	TR
Zaragoza (NE Spain)	Creus et al. (1997)	1560–1600, 1630–1640, 1670–1700, 1710–1715, 1730–1800	TR, i.g.
Zaragoza (NE Spain)	Vicente-Serrano and Cuadrat (2007)	ca. 1635, 1725–1755, 1765–1800, ca. 1825, 1870s, 1900s, 1920s, 1940s, 1960s, 1980s, 1990s	DS, ID
Cataluña (NE Spain)	Barriendos (1997), Barriendos et al. (1998)	1521–1560, 2nd half 18th c.	DS, i.g.
Andalucía (S Spain)	Rodrigo et al. (1999, 2000)	1501–1589, 1650–1775, 1938–1997	DS
Spain	Rodrigo and Barriendos (this volume)	Spring: *Barcelona (NE Spain):* 16th c., 2nd half 17th–1st half 18th, 1st half 20th. *Murcia (SE Spain):* 1675–1725, 1775–1825, 1840–1875, 1900–1940 *Sevilla (S Spain):* 1560s, 1670s, 1750s, ca. 1815–1860, 1990s, late 20th c. Annual: *Bilbao (N Spain):* 1640s, ca. 1660–1740, 1780–1830, 1890s, late 20th c. *Zamora (NW Spain):* ca. 1625–1645, 1660–1700, 1700–1725, 1725–1800, 1st half 20th c., 1970–2000 *Toledo (central Spain):* 1555–1570, 1600–1615, 1720–1760, 1780–1800, 1820s, 1920s, 1950s, late 20th c.	DS
Spain	Martín-Vide and Barriendos (1997)	1566–1567, last third of 18th c.	DS
Spain	Manrique and Fernández-Cancio (1999, 2000)	1664–1693, 1874–1903, 1904–1933	TR
N Morocco	Till and Guiot (1990)	1499–1542, 1575–1596, 1607–1663, 1680–1694, 1714–1759, 1779–1798, 1805–1835, 1858–1887	TR
S Italy	Diodato, N. (2007)	[1680–1695], 1710–1797 (1710–1740, 1755–1797), [1820–1840, 1850–1875], 1920–2002 (1920–1955, 1990–2002)	DS, i.g.
N France	Masson-Delmotte et al. (2005)	1650–1700, 1760–1780, 1800s, 1880–1925, 1950s, 1990–2000	TR (isotopes), i.g.
Mediterranean	Guiot et al. (2005), Brewer et al. (2007)	1500–1665 (1500–1520, 1535–1560, 1590–1605, 1615–1640, 1645–1665), [1765–1780, 1850–1870, 1920–1935, 1940–1960], 1980–2000	TR, M, i.g.

Concerning the 1576–1800 period, seasonal analysis improves its characterization allowing the identification of several stages during this phase (Fig. 7b, c).

Visual inspection of the record of the 1576–1624 period shows two very similar peaks at annual level (Fig. 7b) but the seasonal decomposition reveals that the "a" peak is supported by severe spring droughts whilst while the "b" peak is composed by droughts in all the seasons (Fig. 7c). Considering that spring rogations are easier to trigger than during the other seasons, it is evident that the "b" peak means a drier period than the "a" peak.

Something similar happens for the 1625–1718 period. On an annual scale "c" and "d" peaks are very similar, but on a seasonal scale the "c" peak collects rogations in all the seasons (including the highest values for summer, a season with low weight in farming) while the "d" peak is mostly supported by spring rogations.

For the 1719–1800 period four annual peaks are identified. The "e" and "f" peaks are very similar on a seasonal scale as both are supported by autumn and winter rogations while spring rogations are secondary. The "g" and "h" peaks are relatively different as in both cases the winter pro-pluvia period are short but while in the "g" peak the autumn period is meaningful, the "h" peak is mostly supported by the summer rogations.

This characterization allows to precise the boundaries derived from the annual analysis:

1) 1506–1575: few droughts (values below the average) distributed along most of the year except for summer.
2) 1576–1600: main pro-pluvia periods correspond to spring.
3) 1601–1775: it is the driest period. There were more or less continued rogations for all the seasons. It is composed by three stages:
   a) 1600–1675 (early stage): it presents the most extreme values of the whole series. Pro-pluvia periods appear frequently in all the seasons.
   b) 1676–1710 (middle stage): it roughly coincides with the Maunder Minimum (1675–1715). It is characterized by climatic bonanza that it is only broken by some spring and few summer pro-pluvia periods.
   c) 1711–1775 (late stage): droughts are present in all the seasons except for summer.
4) 1775–1810: few droughts are recorded during this period but for some summer and few spring rogations.
5) 1810–1900: there are almost no meaningful pro-pluvia periods but for a short subdued episode around 1850–60 when short pro-pluvia periods appear in summer and autumn.

4.2. Comparison with other areas in Spain and around the Mediterranean region

Other records around Spain and the Mediterranean area are presented in Table 3.

For Spain, the series located in the interior (Toledo, Haro, Zaragoza, Zamora) show overlapping dry periods but with different duration and initial dates.

Differences increase when we consider the coastal and southern locations (Bilbao, Cataluña, Murcia, Sevilla). In this case, dry periods can be simultaneous to wet periods in other places (as the case of Barcelona and Sevilla, Rodrigo and Barriendos, this volume).

It is remarkable that the case of the 16th century as for interior locations the dry period is restricted to the last third of the century but for the coastal and southern areas it was dry almost the whole century.

The same situation happens during the change between the 17th and 18th centuries. In this period, Toledo, Haro and Zaragoza show an increase in rainfall whereas the dry conditions were continuous in the transition from one century to the other in Andalucía, Barcelona, Murcia, Bilbao and Zamora.

For the 19th century differences are notable among Sevilla and Murcia and the rest of locations as, for these cities, this century shows dry conditions for the first two thirds of the century while these conditions arrive to the other locations towards the end of the century.

That spatial variability has been also found in studies about the 20th century droughts. Santos et al. (2000) divided the Iberian Peninsula in Atlantic Iberia, Central Iberia and Western Mediterranean domains. Olcina (2001) differentiated four climatological settings related to

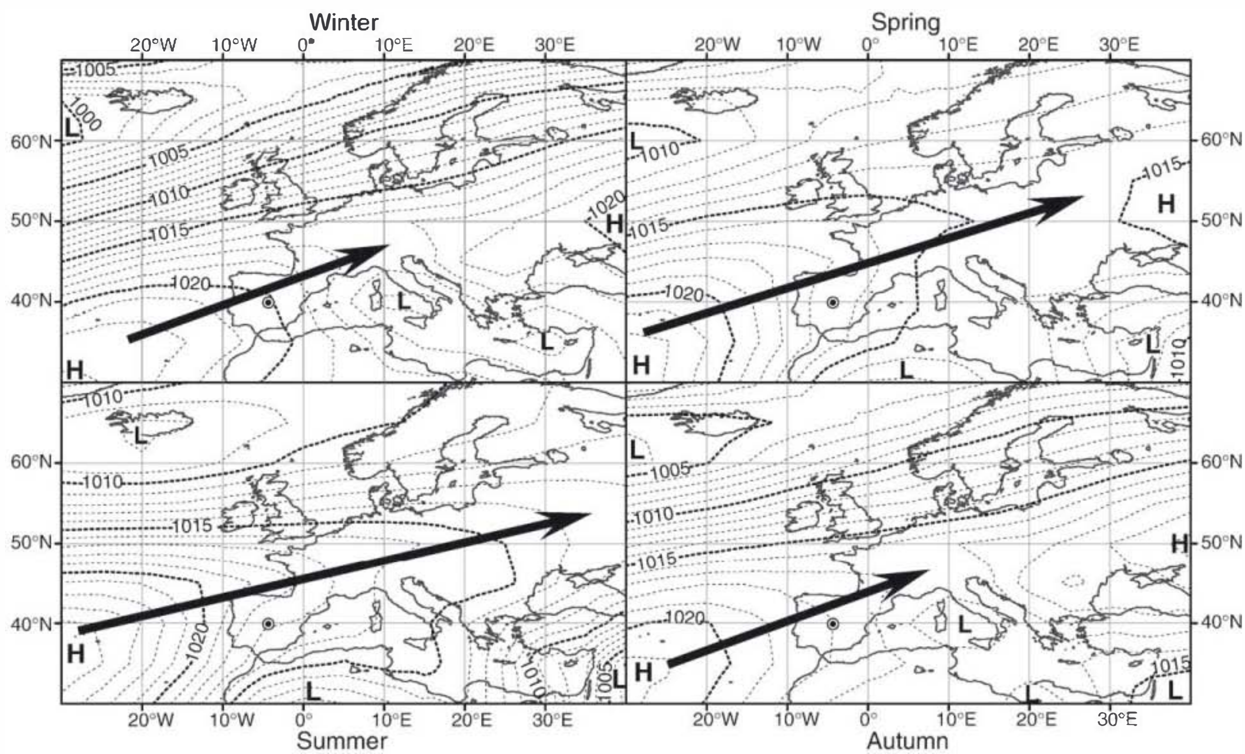

Fig. 8. Mean seasonal sea level pressure (SLP) map for years with pro-pluvia periods (1506–1900 A.D. period). Curve equidistance: 1 mb. L: low pressure areas, H: high pressure areas.

drought: the Atlantic domain, the Mediterranean, mixed Atlantic–Mediterranean and an inland domain. Cuadrats and Vicente-Serrano (2004) found differences among the North, North-East, South-East and Central-Western regions. Lana et al. (2006) found a N–S gradient in the length of the dry spells with some deviations in the vicinity of the Mediterranean Sea and the Atlantic Ocean. Vicente-Serrano (2006) realized that for short drought time scales (1 to 3 months) the Iberian Peninsula can be split in homogeneous classes, but as the time scale increases (12 to 36 months) the spatial complexity increases too, being impossible to define homogeneous regions.

When comparing to other points around the western Mediterranean, these show patterns similar to those of the coastal and southern areas of Spain, except for the N Morocco series (Till and Guiot, 1990) and the drought reconstruction for the Mediterranean region of Guiot et al. (2005) and Brewer et al. (2007) that seem to be a mixture of both inland and coastal Spain.

4.3. Atmospheric situations in relation to drought events

Rainfall in central Spain has been related to transient low pressure systems with Atlantic origin (Zorita et al., 1992; Trigo et al., 2004a) while dry conditions, or lower than average precipitation, have been ascribed to large-scale anticyclonic circulation types (Trigo and DaCamara, 2000; Goodess and Jones, 2002). The topographical closure of this area to the east and the smoother topography to the west (Fig. 1) imply a greater influence of the cyclogenesis of Atlantic origin than of Mediterranean origin.

Esteban-Parra et al. (1998) analyzed the precipitation anomalies in Spain for the 1880–1992 period and identified a main EOF (Empirical Orthogonal Function) centred in Andalusia and the interior of Spain, relating low precipitation to high values of Azores central pressure or an eastward shift of its mean position and positive values of the NAO index and strong westerlies. They point that westerlies are not associated with rain in the Iberian Peninsula as they need an intensification of the high pressure in western Iberia, producing blocking situations over it. The influence of the Atlantic cyclogenesis is reaffirmed by Marshall et al. (2001) and Paredes et al. (2006) who indicate that the preferred location of the Atlantic storm-track paths is controlled by the NAO pattern.

The relation of rainfall in Spain to the NAO pattern has been showed by several researchers (Trigo and DaCamara, 2000; Rodrigo et al., 2000; Goodess and Jones, 2002; Trigo et al., 2004b) and Trigo et al (2004a) attributed dry winter conditions to a northern extension of the Azores high.

However, precipitation changes have been also linked to the ENSO (Rodó et al., 1997; Morala et al., 2003; Knippertz et al., 2003), to the Eastern Atlantic and Western Russia patterns (Rodríguez-Puebla et al., 2001), to other patterns (Pauling et al., 2006), or to a blocking Atlantic mechanism and the East Atlantic Jet as more representative than the NAO (Martín et al., 2004), covering a wide spatial range of patterns.

Looking to the atmospheric situations in relation to drought events, maps of sea level pressure (SLP), using the data of Luterbacher et al. (2002a), were elaborated for the documentary period averaging the SLP by season over years with rogations (Fig. 8).

Table 4
Seasonal correlation of the pro-pluvia period against NAOi reconstructions of Luterbacher et al. (2002b) and Cook et al. (2002) for 1506–1900 A.D.

			Pro-pluvia period			
			Winter	Spring	Summer	Autumn
NAO Index	Luterbacher et al. (2002b)	Winter	−0.0480	0.1875*	−0.4293	0.0492
		Spring		0.1204	−0.3795	0.1210
		Summer			−0.2240	−0.2716
		Autumn				0.0078
	Cook et al. (2002)	DJFM	−0.1903	0.2461**	0.1785	0.1768

*: $p<0.1$; **: $p<0.01$ (other cases: $p>0.1$).

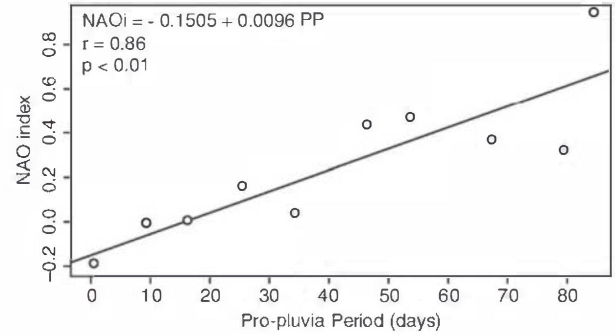

Fig. 9. Lineal regression of the spring and autumn pro-pluvia periods indexes for Toledo (values grouped in 10-dayintervals) for the period 1506 to 1900 against the reconstruction of the NAO index (Cook et al., 2002).

These maps show that from the 16th to 19th centuries the most common synoptic pattern for droughts on all the seasons corresponds to ridges of marine tropical air masses entering from the Atlantic to Europe. The 1015 mb isobar is always located around the south of England and the "Icelandic" lower pressures move from 55°N to 60°N. However, there are differences among seasons. Spring and summer are characterized by Iceland–Azores pressure gradients varying from 10 mb (spring) to 16 mb (summer) and Azores–Lisbon gradients ranging from 4.5 mb (spring) to 6.5 mb (summer), and two centres of lower pressures located in North Africa and the Near East. For winter and autumn the Iceland–Azores pressure gradient fluctuates from 19.5 mb (winter) to 15.5 mb (autumn), the Azores–Lisbon gradient is 1–1.5 mb (winter) to 2 mb (autumn), and the lower pressures locate in a shallow trough extending from Cyprus to the Tyrrhenian Sea, cutting the Atlantic Ridge that nearly only affects the Iberian Peninsula.

Seasonal (Fig. 8) and monthly reconstruction of SLP show that, during drought periods, the Azores high remained stable at a location around 30°–35° N and 25°–30° W, similar to the situations described by Esteban-Parra et al. (1998) and Trigo et al. (2004a), causing a displacement of the storm fronts to a northern position. The synoptic patterns showed in Fig. 8 are comparable to the positive phase of the North Atlantic Oscillation (NAO) (Hurrell, 1995).

Comparison for the non non-instrumental period (1506–1900 A.D.) of the pro-pluvia period index and the reconstructions of the NAO index of Luterbacher et al. (2002b) and Cook et al. (2002) provides a weak correlation (Table 4) although it reflects the connection between the winter or DJFM NAO index and the spring rainfall. This relation improves if we group the pro-pluvia period values in intervals. Fig. 9 shows the relation between the spring and autumn pro-pluvia period values grouped by intervals of 10 days, and an additional interval for the 0 value, and the DJFM reconstruction of the NAO index of Cook et al. (2002).

These relations demonstrate that the North Atlantic Oscillation is one of the mechanisms that influence drought development in central Spain since 1506.

This result is compatible with the more wide scale schemes as those of Zorita et al. (1992), González-Rouco et al. (2000) or Xoplaki et al. (2004) who, for a regional analysis, still recognize the weight of local factors, weight that increases as we reduce the spatial scale.

5. Conclusions

Rogations are a valuable method to estimate droughts in historical climatology. Commonly used annual weighted sums bias the results towards the spring rogations which are triggered by less severe droughts than in other seasons due to their relation to farming activity.

31-year running average of processed data allows to identify longer trends despite the method used for the analysis of rogations (simple sum, weighted sums, length of rogation periods). But it filters higher frequency signals which are lost.

The proposed pro-pluvia periods method offers some advantages in comparison to the previous methods used in rogation analyses:

1. Distribution of rogation weights is continuous instead of discrete (as using levels attributed on basis to liturgical acts). This reduces the influence of local/regional factors and cultural or social uses and it provides a more objective scale.
2. The relation between the pro-pluvia period and the drought length allows to obtain an approximation of the length of the drought events on an intraannual basis.
3. Annual to longer time scales analysis of these data can be characterized more precisely by using seasonal data.

Implementation of this method on the rogation series of the Toledo Cathedral Chapter allows to describe thoroughly the drought evolution for this period and to characterize the 1506–1900 period in this region:

4. There is an increase in the number of droughts for all the seasons and their length for the 1601–1775 A.D. period. The accumulation of autumn rogations for this period is especially meaningful.
5. For the 1676–1710 A.D. period, there is an evident shortening of the length of droughts that are mostly placed in spring. This "normality" in rainfall has been also described by Alcoforado et al. (2000) for southern Portugal and by Barriendos (1997) for the Iberian Peninsula from rogation data.

Despite the results and temporal resolution, it must be stressed that the use of pro-pluvia rogations gives only information about drought periods and not about rainfall in general. Consequently, comparison with other records must be carried out carefully. Moreover, the 17th to 18th centuries period is characterized by periods when floods and droughts alternate quickly and the reconstruction provided here is just the record of a part of such phenomena.

However, we believe that the methodology or working philosophy applied in this paper can be extended successfully to other kinds of historical data. Droughts, heat or cold waves, stormy periods, or any other "long term" phenomena providing a documentary series can be quantified by the period methodology. This can reduce the uncertainty inherent to the individual perception of the phenomena or its overestimation by an accumulation of news about it in a short period.

Despite the presence of commonalities among different locations in Spain and the Western Mediterranean area, there are meaningful differences on the timing and length of drought periods. Variability of the distribution of droughts in time and space stresses the need to increase the number of records and their lengths in order to improve the regional reconstruction of this phenomenon. Uncertainties about the weight of local and regional patterns must be explored with the help of new reconstructions.

Such spatial heterogeneity is also evidenced by the feeble correlation to the atmospheric patterns, but a certain relation to the NAO can be invoked and this is supported by the dominance of the influence of the Azores pressure high on such events.

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