

## A 500-YEAR PRECIPITATION RECORD IN SOUTHERN SPAIN

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*Received 5 June 1998*

*Revised 30 December 1998*

*Accepted 21 January 1999*

### ABSTRACT

This paper is part of a research programme devoted to the analysis of historical climate in Spain. A reconstruction of rainfall characteristics in Southern Spain from 1500 to the present is described. Weather information was taken from original documentary sources in the region. A numerical index was established to characterize the rainfall and its evolution. Results were calibrated with modern precipitation data and with the results of other studies of historical climate. The main objective is to obtain a long precipitation record. A preliminary analysis of the obtained series shows a fluctuating behavior with alternating dry and wet periods. The wettest periods occurred at the end of 16th century, the beginning of 17th century, and at the end of 19th century. The driest periods in the pre-instrumental era occurred during the first half of the 16th century, and around 1750. A general decreasing trend in precipitation can be observed from 1960 onwards. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Andalusia (Southern Spain); historical climatology; annual rainfall; precipitation index; precipitation anomalies, 1501–1990; precipitation; reconstruction

### 1. INTRODUCTION

Anthropogenic influence on climate overlaps a background of natural climate variability that may diminish or increase it. Paleoclimatic studies are useful in understanding the nature and possible reasons for present climate variations, because they allow the analysis of changes in the relatively short instrumental period in longer-scale perspectives (Berger *et al.*, 1989).

During the last 500 years, the period known as the Little Ice Age (LIA) provides the best chance to research the mechanisms which might affect the climate in timescales ranging from a decade to a century. Although there is no evidence of a long cold synchronous period for the entire globe (Jones and Bradley, 1992), the LIA was the most significant period of glacial development in the last 2000 years. Therefore, its study may enable a better understanding of natural climate fluctuations. Besides, there is plenty of precisely dated proxy data with a good time resolution for this period (Pfister, 1994). Among these, historical documents deserve special attention. In general, they record anomalies and weather extremes, such as droughts and floods, cold waves, storms, etc, which allow us to infer climate fluctuations and anomalies.

Andalusia (Southern Spain, around 37°N) is of unquestionable interest for climate studies as a result of its placing, both geographic and latitudinal, being influenced by westerlies from the Atlantic Ocean and the Mediterranean influence. Rain distribution throughout the year is ruled by the Azores High behavior, which may allow Atlantic cyclones and their associated fronts to cross the region from west to east, or, in the opposite, may delay its movement to the south, invading the Iberian Peninsula and producing drought periods. In addition, the development of winter anticyclonic centers over the region, and local thunderstorms and convective rainfall provoked in summer by thermal lows (Capel Molina, 1975) must

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be borne in mind. The main disturbances are linked to the jetstream behavior and the polar front. As a result of the importance of the polar front dynamics in middle latitudes, the study of this region is of great interest.

This work focuses on the analysis of total annual rainfall in Andalusia from the 16th century up to the present day. Research on historical climate in Spain is relatively young. After some qualitative and descriptive works (Fontana Tarrats, 1977; Mackay, 1981; Alvarez Vázquez, 1986; Font Tullot, 1988), the research focused not only on the analysis of sources but also on the statistical processing of data. The first results of this work (Rodrigo *et al.*, 1995a,b, 1996) focused on rainfall analysis during the 16th and 17th centuries, the period the LIA is supposed to have affected the Iberian Peninsula (Font Tullot, 1988). In the first paper, the methodology of the statistical analysis was established, the second one focused on the reconstruction of a total annual rainfall series, and the third one was devoted to the study of seasonal rainfall variations. During the period in which these articles were published, research was not developed to the point of overlapping the pre-instrumental period with the instrumental one, and results could only be regarded as preliminary. However, similarities to other paleoclimatic studies were noticed both in the Iberian Peninsula (Creus and Puigdefàbregas, 1984; Barriendos, 1994) and abroad (Camuffo and Enzi, 1992; Pavese *et al.*, 1992; Serre-Bachet *et al.*, 1992; Grove and Conterio, 1994). These works discussed the need for expanding the recorded period up to the present, bearing in mind two basic aims: firstly, to calibrate historical indexes appropriately, by comparison with contemporary instrumental series (Rodrigo *et al.*, 1995b); and secondly, delimiting Andalusian climate from the beginning of the LIA up to the present (Rodrigo *et al.*, 1995a). The aim of this work is to propose a complete and uninterrupted series from the beginning of the 16th century up to the present.

The longest instrumental series in Andalusia, relates to Gibraltar and began in late 18th century extending to the present day. This series has already been studied in depth (Wheeler and Martín Vide, 1992) and will be briefly presented in Section 2, in the discussion of its use as a reference weather station for evaluating historical data. The basic hypotheses in this study are: (i) documentary sources give useful information on weather events during pre-instrumental period and particularly on extreme events (Bradley and Jones, 1992; Pfister, 1992); (ii) variability in frequency and intensity of extreme weather events provide the main evidence of changes in mean climate (Wigley, 1985; Katz and Brown, 1992). Taking these basic hypotheses into account, consideration is given to the analysis of documentary sources and the compilation of ordinal indexes which essentially exhibit extreme events during the period under study. The results are compared with other proxy data from both the Iberian Peninsula and abroad (Section 3). Thereafter, calibration of indexes is undertaken by analyzing the overlapping period 1791–1820 (Section 4). The period 1821–1850 is used to validate this calibration (Section 5). With the reconstruction of the rainfall series for the entire period, a preliminary analysis of the resulting series is undertaken (Section 6). The aim is consider the entire period under study with regard to the 'normal' climate in the 20th century. Finally, future study prospects are presented.

## 2. INSTRUMENTAL DATA

The longest instrumental series in the Iberian Peninsula is the rainfall series for Gibraltar, covering the period 1791 to the present. For the period 1791–1850, there is data on total annual rainfall. From this date on, the series is supplemented with seasonal data. In this study, the total annual rainfall has been used. The analysis of seasonal data is postponed until a later work. The general traits of this series are well known, and have been studied in detail. Testing for normality of data, it was determined that this data may not be considered as sampled from a normal distribution (Forster, 1942; Martín Vide, 1989; Wheeler and Martín Vide, 1992). Nonparametric statistics are particularly useful when the distribution of data is unknown or non-normal (Sneyers, 1992). To test the homogeneity of the series, the nonparametric Thom test was performed (Thom, 1966). The Thom test studies the variations of the series with respect to a central value, in particular the median. In this test the number of uninterrupted runs,  $R$ , of values higher and lower than the median is counted. Under the null hypothesis this statistic has an

approximately normal distribution of mean  $E(R) = (N + 2)/2$  and variance  $\text{Var}(R) = N(N - 2)/4(N - 1)$ . The statistic is defined as

$$Z = \frac{R - E(R)}{\sqrt{\text{Var}(R)}}$$

If  $|Z| < 2.58$ , the null hypothesis is verified at the 99% confidence level. In the present case,  $Z = -0.78$ , and it can be concluded that the Gibraltar series is homogeneous.

The first question in this study is to determine whether this series can be considered to be representative of the entire region, i.e. as a reference series for the calibration of historical indexes which are related to the entire Guadalquivir Valley area (Figure 1). Table I compares basic descriptive statistics from the Gibraltar, San Fernando, Seville and Granada series. The San Fernando series covers the period 1841–1990, the Seville series 1871–1990 and the Granada series 1940–1990. It is evident that the Gibraltar values are markedly higher than those of other stations for all calculated parameters, except for the coefficient of variation. This parameter, defined as the ratio between the standard deviation and the mean of the series, is a measurement of the variability of the series, and may be useful to compare two samples. Therefore, it seems that as far as variability is concerned, the Gibraltar series is analogous to those of San Fernando or Seville. This poses no problem in the case of calibration, because most of the historical information refers to the Guadalquivir Valley. However, this parameter is suitable when data

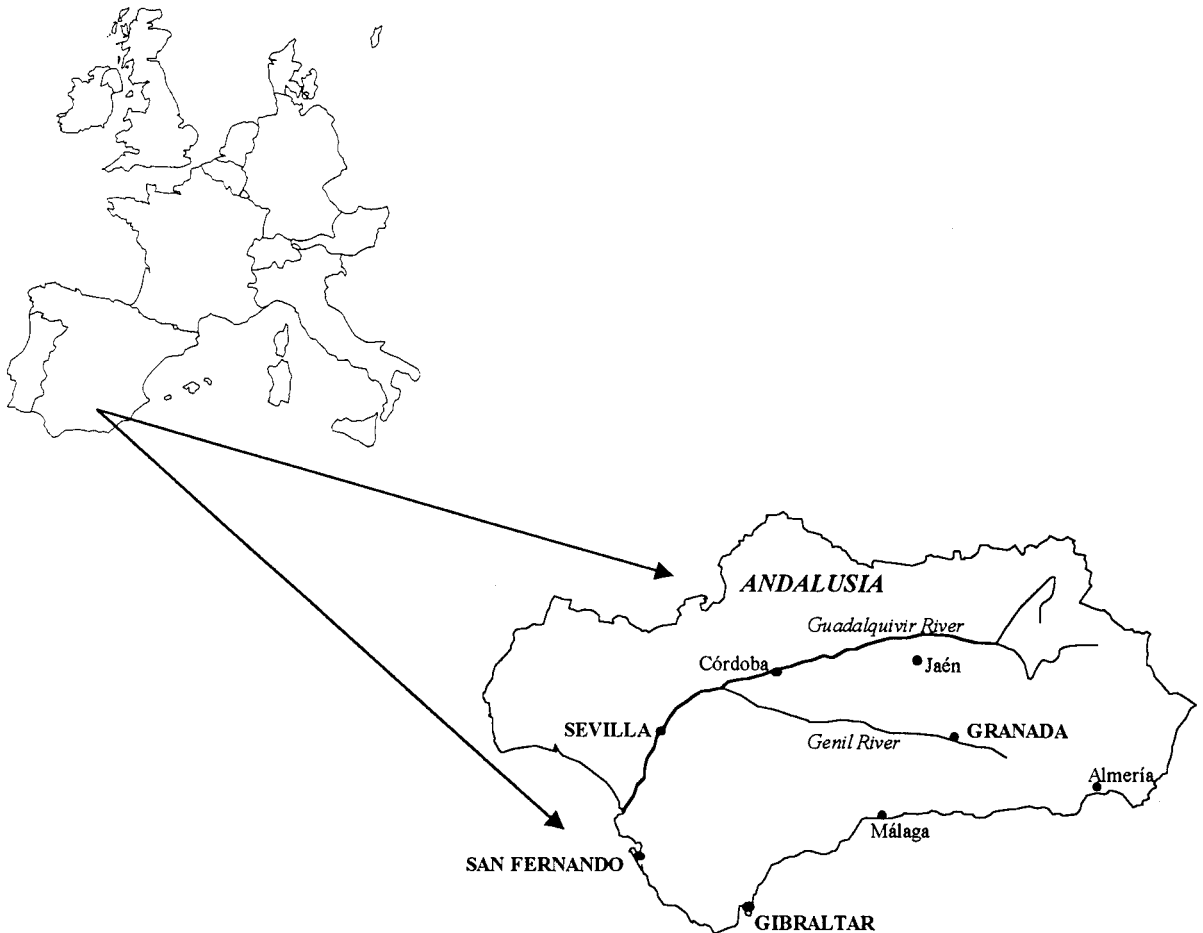


Figure 1. Map of the study region

Table I. Comparison of the annual precipitation (mm) in Gibraltar, San Fernando, Seville and Granada

Parameter	Gibraltar	San Fernando	Seville	Granada
Average	824	611	561	398
Mode	793	524	546	391
Median	793	568	549	391
S.D.	256	195	178	89
Minimum	357	300	159	227
First quartile	654	466	438	344
Third quartile	955	713	657	459
Maximum	1831	1273	1063	629
Variation coefficient	31%	32%	32%	22%

have a normal distribution. Unfortunately, the series of this study are non-normal. In such a case, nonparametric methods are advisable. Among these methods, the calculation of the Spearman coefficient provides a measurement of the correlation between two samples. In this method the original observations  $x_i$ ,  $y_i$  are replaced by the rank which is assigned to them when they are arranged in increasing order of magnitude,  $x'_i$  and  $y'_i$ , respectively. The coefficient can be calculated by means of the formula:

$$r = 1 - \frac{6}{N(N^2 - 1)} \sum_{i=1}^N (x'_i - y'_i)^2$$

Under the null hypothesis (no correlation), the distribution of this quantity is asymptotically normal with  $E(r) = 0$ , and  $\text{Var}(r) = 1/(N - 1)$ . The null hypothesis is rejected for large values of  $|r|$ . The significance level is obtained by means of a standard normal distribution table (Sneyers, 1990). In the present case, the correlation coefficients are 0.71 with San Fernando, 0.61 with Seville and 0.45 with Granada, all of them statistically significant at the 95% confidence level.

In previous work (Esteban-Parra *et al.*, 1997; Castro-Diez *et al.*, 1998) a more detailed study of rainfall variability in the southern half of the Iberian Peninsula was undertaken. For the period 1945–1990, 134 series were analyzed and an Empirical Orthogonal Function (EOF) analysis was applied. This method allows the synthesis of a very large data set, grouping them in a few regions with similar variability characteristics. On the other hand, it is possible to eliminate a lot of local noise as a result of microclimatic or nonclimatic factors, putting aside those patterns (EOFs) with small variances. The selection of the significant patterns was made according to the method described by Preisendorfer (1988), resulting in three significant patterns. The first one explains 52.28% of the total variance, the second 13.70% and the third one 6.16%. In order to obtain a better visualization of the results, Figure 2 presents the isolines corresponding to the correlation coefficients between the data of each individual station and the EOFs. The first EOF represents the western area, the second the central area and the third the eastern one. As can be seen, Gibraltar is situated in the region influenced by the first EOF, covering the Peninsular south-west and the Guadalquivir Valley, where rainfall is basically due to Atlantic weather types. The second EOF represents the mountainous Sierra Nevada area and middle valleys. Finally, the south-east is represented by the third EOF. Rainfall in this area is mainly a result of convective mechanisms, which are associated with easterly flows from the Mediterranean. The second EOF represents a transition area between the one dominated by the Atlantic flows and the region dominated by the Mediterranean influence. On the other hand, time evolution of rainfall in the three regions is similar, as shown by the significant correlations between the three time EOF series (Esteban-Parra *et al.*, 1997).

Accepting that the EOF method provides a variability analysis of a large set of series, it may be concluded that Gibraltar can be considered as representative of the Peninsular south-west and the Guadalquivir Valley, and to some extent the entire region. Its use is thereby acceptable with respect to this study.

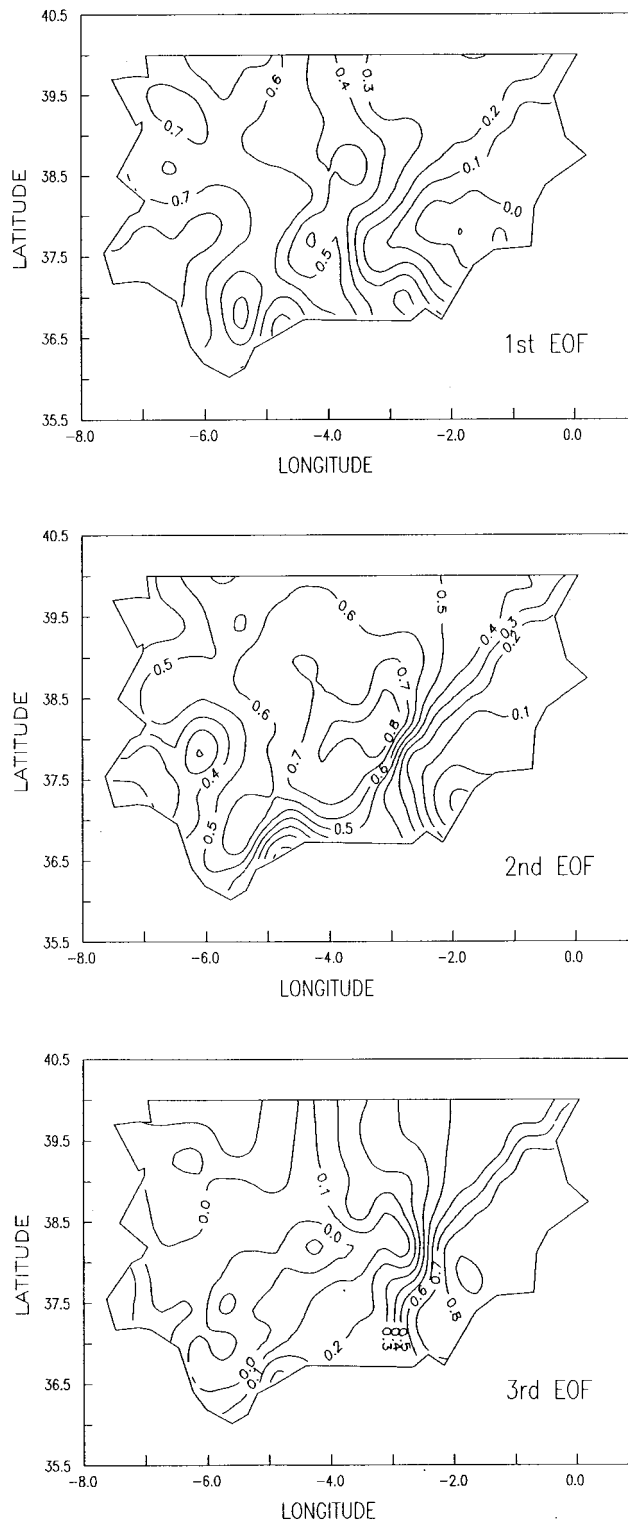


Figure 2. EOFs for annual precipitation in Southern Spain, 1945–1990. Gibraltar is situated in the south-west, corresponding to the first EOF, that amounts to 52% of the total variance

### 3. HISTORICAL DATA

#### 3.1. Data sources

Historical weather records have been obtained by the rigorous analysis of original documents from a variety of sources: urban annals (UA); city histories (CH); general histories of Spain (GH); religious chronicles (RH); brief reports of events and letters (R); and books of church and city archives (A). The advantage of using different kinds of sources lies in the fact that both the aim and character of the texts varies depending on their type. This allows for an adequate cross-comparison of news collected, assists in eliminating faults and in comparing information from different documents. Consequently, such methodology partially eliminates the subjectivity inherent in this kind of documentation (Ingram *et al.*, 1981). Furthermore, the information obtained has been compared with the data from two modern compilations (Fontana Tarrats, 1977; Font Tullot, 1988) and a new category (RS) relating to Manuel Rico Sinobas' 19th century pioneering work. The treatises of Rico Sinobas represent not only the first attempt at systematic research in historical climatology in Spain, but also the first rigorous climatological work. For the moment, only those manuscripts of Rico Sinobas providing descriptive information during the first half of the 19th century in Andalusia have been analyzed.

The criteria followed in analyzing the reliability of sources are time–space closeness to the event, liable transmission of oral or written information, cross-comparison of information from different sources, a good agreement among contemporary proxy data, such as agricultural production, and the conciseness of authors in describing well known nonweather events, e.g. military and political events, plagues, famine, epidemics, eclipses and earthquakes. Table II lists the data sources used indexed according to a set code detailed in the Appendix.

The authors of chronicles were priests, lawyers and merchants of a similar cultural level. All witnessed the reported events or made a reliable record of their information from oral or written sources. Most of them lived in Andalusian cities and were used to the 'normal' behavior of Andalusian climate.

In general, a variety of sources are available for more than 1 year in most of the studied period. Table III presents the number and nature of sources assessed for each century within the total period under study. Different sources are available in each century. The shortage of sources in the 19th century is as a result of the fact that only the first half of the century was analyzed. The information was mainly contrasted with the set of documents included in Class A, books of church and city resolutions. Civil and religious institutions recorded daily activities, resolutions and any event which could disturb everyday life in town or surrounding rural areas. Class R comprises similar private documents (letters), and the so called 'relaciones' or reports, forerunners of modern newspapers. These documents were published just after the event occurred and have a high reliability. Sources R-7 to R-10 are the first newspapers published in Andalusia in late 18th and early 19th century. Class R together with minutes records (Class A) are an important reference for checking the information gathered from other sources.

Many documentary sources remain to be explored in the context of paleoclimatic research. However, analysis of information contained in the available documents allows the opportunity to present interesting results relating to past climate variability in Andalusia.

#### 3.2. Database

The processing of compiled reports began by their codification. This allowed the ordering of information in time–space and type (rain, thermal, wind, cloudiness) scales. Most data relates to Seville and the Guadalquivir Basin, Málaga on the Mediterranean coast and Granada together with Sierra Nevada mountains (Figure 1). The majority of the data corresponds to rain-related phenomena, basically extreme events, such as droughts, storms and floods. The high percentage of this kind of information (approximately 70%) encouraged focusing attention on the analysis of the rainfall regime. Time coverage of these information is summarized in Table IV. Rain-related descriptive information covers up to 91% of the years in the entire period, amounting 2.75 items year<sup>-1</sup>. The information increase in the 19th century is due basically to Rico Sinobas' work (instrumental data not taken into account here). Provided the

Table II. Time coverage of the data sources

Source code	16th Century	17th Century	18th Century	19th Century
UA-1	1588, 1590	1603–1646		
UA-2	1600	1601–1678, 1680, 1684, 1691, 1692		
UA-3	1501–1600	1601–1700		
UA-4			1730–1800	1801–1835
UA-5		1671–1700	1701–1746	
UA-6	1501–1600	1601–1700	1701–1789	
CH-1	< 1598			
CH-2	< 1600			
CH-3	< 1600			
CH-4		< 1628		
CH-5			< 1762	
CH-6	< 1587			
CH-7			< 1794	
CH-8			1704–1766	
CH-9				1801–1845
GH-1	1501–1600	1601–1621		
GH-2	1516–1600			
GH-3		1699–1700	1701–1711	
RH-1		1604–1605		
RH-2	1501–1600	1601–1633		
RH-3	1583–1600	1601–1681		
RH-4		1615–1652		
RH-5	1554–1600	1601–1669, 1678–1700	1701–1742, 1762–1765	
RH-6			1756–1767	
R-1	1561–1569			
R-2	1554, 1560, 1576, 1582, 1585, 1586, 1588, 1589, 1590, 1599, 1600	1602, 1608, 1610, 1617, 1656, 1668		
R-3		1604, 1618, 1626, 1628, 1629, 1636, 1651, 1653, 1661, 1671, 1680, 1681, 1684		
R-4		1629		
R-5			1764–1765	
R-6		1634–1648		
R-7			1796–1797	
R-8			1797, 1799, 1800	
R-9			1800	
R-10				1813
A-1	1501–1600			
A-2	1522, 1557, 1566	1604, 1614, 1618		1801–1810
A-3	1560–1600			
A-4	1575			
A-5	1587–1600	1601–1700	1701–1793	
A-6	1507–1599			
A-7	1490–1518			
A-8			1764, 1776	1804
RS-1				1801–1850
RS-2				1801–1850

< Indicates information previous to the corresponding year, analogous for >, but for later information than this year. The source codes are indicated in the Appendix.

Table III. Number of sources and types of sources for each century

Type of source	16th Century	17th Century	18th Century	19th Century
UA	4	5	3	1
CH	4	3	3	1
GH	2	2	1	
RH	3	5	2	
R	2	4	4	1
A	7	2	2	2
RS				2
Total	22	21	15	7

extreme character of events, this information density is sufficient to enable a meaningful analysis. Development of research and future enlargement of the database will obviously enable a more precise temporal calibration of information. The lack of a complete database represents a serious problem for historical climatology that can only be alleviated as and when the database is enlarged following further archive research. Meanwhile, works on historical climatology must be seen as contributions on a continuum to the understanding of past climate and their conclusions must be carefully appraised.

### 3.3. Rainfall index

The designing of an ordinal index was integrated into the estimation of extremes. The main rain-related events were indexed as follows: hydrologic droughts (absence of rain together with information on drops in river and water spring levels, dry wells, etc),  $-2$ ; weather droughts (absence of rain without additional information),  $-1$ ; hard and/or constant rain,  $+1$ ; rain-induced flood,  $+2$ . When sources did not comment on weather conditions, the situation was regarded as normal and given a 0 value. This value was also allotted to news that may be regarded as normal according to 20th century standards, e.g. simple comments on April or November rains, normally the wettest months at present.

These numeric values were assigned to each place and month of the year. The monthly regional index was obtained by averaging the monthly values corresponding to each locality. Subsequently, a seasonal index was obtained by averaging monthly values considering the number of months with relevant news. The agricultural seasons of the year were considered. These seasons are winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). This space-time averaging procedure allows the filtering of strictly local news and the partial elimination of heterogeneity in records related to space news distribution and the chroniclers' doubts about the described news. Positive values mark a season with a wet anomaly, and negative ones a dry season. Value 0 suggests absence of remarkable events or an opposite event in the season under study, which could indicate intraseasonal variability. This is a factor that can only be solved by adequately enlarging the database, an unending task provided that new documentary sources with relevant information may always appear. The percentage of seasons with an  $I \neq 0$  index value was 21.5% in the 16th, 33% in the 17th, 18.5% in the 18th and 24% in the first half of the 19th century. For the entire period, the

Table IV. Number of years with relevant climatic information and density of information for each century and the total period 1501–1850

Period	Number of years	Items year <sup>-1</sup>
1501–1600	85	2.3
1601–1700	95	2.5
1701–1800	87	2.6
1801–1850	50	4.3
1501–1850	317	2.75

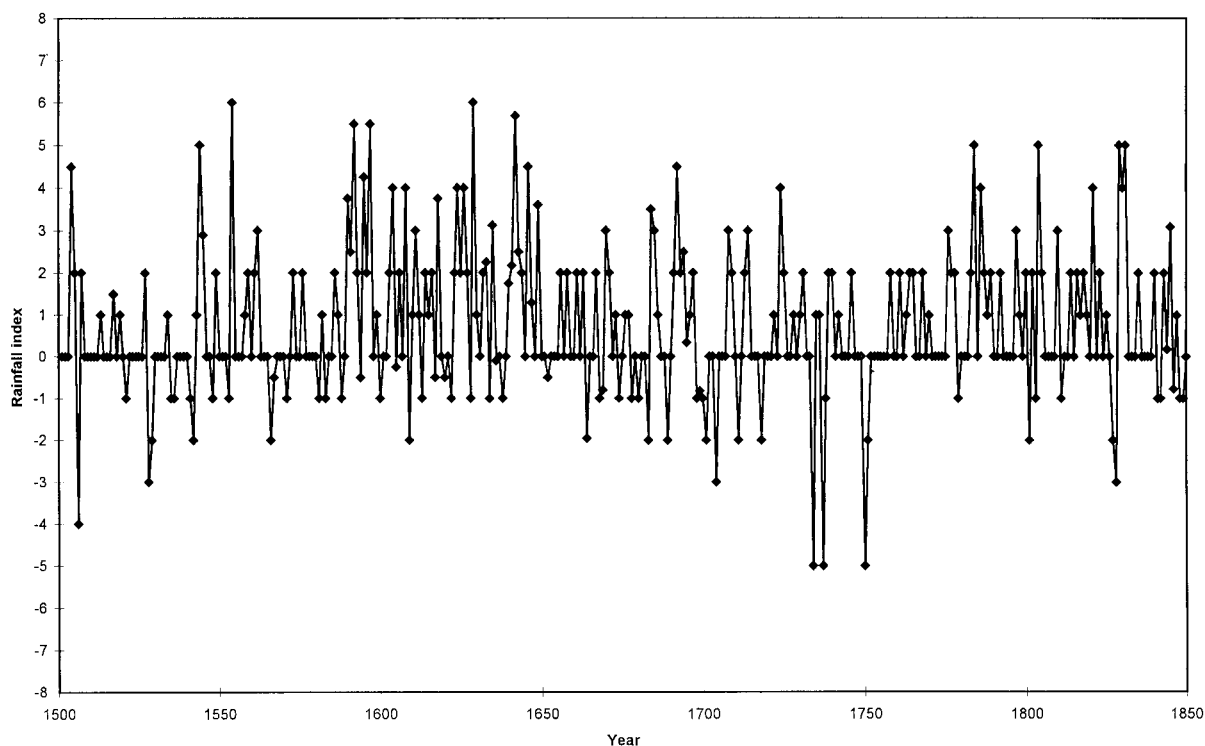


Figure 3. Annual precipitation index for Andalusia during the period 1501–1850 (index obtained from qualitative information, instrumental data are not considered in this Figure)

percentage was 24.28%. As the information during the 19th century comprised of a higher density (Table IV), these values provide greater reliability in affirming the main weather phenomena of the past. The information varies seasonally, with 35% of news in winter, 31% in spring, 25% in autumn and 9% in summer. This distribution is a result of the interest of chroniclers in everything affecting the state of agriculture and evolution of crops, especially wheat sown in autumn and harvested in early June. These indexes must be interpreted as a measure of the behavior of weather anomalies or extreme phenomena, rather than average values of the analyzed variables, provided the character of reports, based on exceptional or socioeconomically impacting events. The annual index is the sum of the four seasonal indexes. Its value ranges from  $-8$  to  $+8$ , although lack of news relating to the summer prevents such extreme values being reached.

A variety of indexes have been proposed in historical climatology studies. Difference indexes, as those used by Lamb (1977) for winter harshness ( $C - M$ , where  $C$  and  $M$  are the number of unmistakably cold and mild months in a decade, respectively), are highly sensitive to changes in the place of observation and lost data. In contrast, rational indices, e.g.  $(R - D)/(R + D)$ , where  $R$  is the number of floods and  $D$  the number of recorded droughts (Yao, 1982), exhibit less sensibility and tolerate gaps and doubts in the perception and/or real frequency of extreme events (Ingram *et al.*, 1981). The index used here can be regarded as being of the rational type, as it is the result of an averaging process between positive and negative values of anomalies. In this sense, it is very similar to the unweighted indexes proposed by Pfister (1992), where three levels are established for month data ( $-1$ ,  $0$ ,  $+1$ ) to indicate positive and negative deviations from the class defined as average. Seasonal index ranges from  $-3$  to  $+3$  and the annual index from  $-12$  to  $+12$ . In the present case, provided that the majority of news has a seasonal precision, no matter which particular month in the season, the described index was preferred. Although less detailed, it allows inference of information on rainfall fluctuations with at least seasonal precision. Figure 3 displays the index for the period 1501–1850.

### 3.4. Comparison with other data

Results can be contrasted in several ways; comparison with historical observations from other regions, with other proxy data and independent instrumental weather observations. The definitive proof of accuracy is agreement with instrumental data contemporary to the analyzed period. In the present case, this is only possible for annual rainfall from 1791, and will be considered later.

In concordance with other data series, considerable literature exists relating to conditions during the LIA in different parts of the world. In general, this period can not be regarded as uniform and constant with respect to its timescale. Even the dating of LIA remains an open question (Jones and Bradley, 1992; IPCC, 1996). Existing research, however, contributes some guidelines. In the Iberian Peninsula, the study of grape-harvest dates in Valladolid (Castille) during the 16th and 17th centuries (Benassar, 1967) indicates a maximum in rainfall around 1620–1630 and an important dry period in 1675–1690. The analysis of rogations in Catalonia (north-east of the Peninsula) suggests a dry and arid period between 1530 and 1550, a cold wet era from 1570 to the early 17th century, and further dry periods in 1630–1640 and significantly around 1680, with wetter conditions at the beginning of the 18th century (Barriendos, 1994). Climatic conditions in the Iberian Peninsula during the LIA must have been similar to those of the Mediterranean area, especially France and Italy. Le Roy Ladurie (1983) identified a dry cold period during 1639–1643 from the analysis of dates of grape harvests in Southern France. The joint analysis of grape harvest dates and ice progression in the Alps lead Le Roy Ladurie to highlight the period 1640–1653 as one of the coldest and wettest ones in the historical period, characteristic of the LIA conditions in western Europe. In Northern Italy, Camuffo and Enzi (1992) discovered an increase in the frequency of cold harsh winters and high instability in atmospheric conditions in 1570–1614. Increased rainfall and frequent floods at the end of the 16th century are also reported in Switzerland (Pfister, 1992) and Low Franconia (Glaser and Hagedorn, 1991). Northern Africa recorded wet conditions from the 16th to the 18th century, with significant dry periods in the 1680s, 1740s and 1750s (IPCC, 1996). Briffa *et al.* (1990), from the analysis of tree rings in Fennoscandia, discovered a remarkable cold period between 1570 and 1620, thus matching the wettest period shown in the data presented here. Andalusian data (Figure 3) are similar to published data referring to other regions, although they might present slight time variations.

## 4. CALIBRATION

The calibration of the indexes poses the following difficulties:

- (i) The index is a regional one, because information from the entire region has been considered, whereas instrumental data are local and refer exclusively to Gibraltar. This problem however has been partially addressed as outlined earlier (Spearman correlation coefficients between Gibraltar and other stations and EOF analysis).
- (ii) Although the reference station (Gibraltar) seems to behave in a similar manner to other Andalusian stations, the instrumental readings are consistently greater. Thus, calibration is meant as an appropriate means for interannual variability rather than for rainfall absolute values. This fact led to the analysis of anomalies regarding the average value, in place of rainfall total values.
- (iii) Instrumental data are annual ones, so rainfall at a seasonal scale cannot be calibrated. This limits the calibration to the annual index. Seasonal analysis is postponed to a further study.

In order to calibrate indices, the total overlapping period 1791–1850 was divided in two subperiods of 30 years each, corresponding to the WMO-suggested length for the analysis of 'normal' characteristics in weather variables. The first subperiod 1791–1820 was used for calibration purposes, whereas 1821–1850 was used for the verification of results.

In the case of calibration period, the comparison was established between the index values and rainfall anomaly values in mm in relation to the average rainfall for the entire overlapping period. As can be seen in Figure 4, clear similarities can be observed in the maxima and minima corresponding to the 1801 and

1811 droughts, as well as maxima corresponding to the years of 1797, 1800 and 1804 when rain was abundant. These examples prove how the calibration period collects different possibilities in designing the index, including years which can be considered as 'normal', when the index value is 0. The differences noticed between both series (index and instrumental data) owe to the fact that the instrumental series is a local one, whereas the indexed series refers to the entire region.

The comparison was made by computing the correlation coefficient between the Gibraltar instrumental series and the indexed regional series. Because of the non-normal character of the series, the non-parametric Spearman correlation coefficient was computed. The result is 0.38, statistically significant at the 95% confidence level. Therefore, there is a non-zero correlation between instrumental data and indexes. The main purpose is to obtain a relation between instrumental anomalies and indexes. A linear model was adopted. Using the index as the independent variable and measured rainfall anomalies as the dependent variable a linear relation given by:

$$P = a + bI$$

was obtained, where  $P$  corresponds to the value of total annual rainfall anomalies in mm and  $I$  to the index value. The correlation coefficient value, 0.56, proved to be statistically significant at the 95% confidence level by means of a  $t$ -test. The estimate of parameters for the regression fitting gave the results  $a = -70$  mm,  $b = +100$  mm with the 95% confidence level error given by  $\Delta a = \pm 40$  mm,  $\Delta b = \pm 30$  mm. Although it is statistically significant, the correlation value is not too high, basically because a local instrumental series is correlated to a regional index series.

The equation obtained allows the determination of the values of estimated rainfall anomalies  $P_e$  from index values. In order to confirm if estimations are coherent with instrumental data, percentile distribution of instrumental rainfall anomalies for the overlapping period (1791–1850) were studied. The aim is to classify years as very dry ( $P < P_{10}$ ), dry ( $P_{10} \leq P < P_{25}$ ), normal ( $P_{25} \leq P < P_{75}$ ), wet ( $P_{75} \leq P < P_{90}$ ) and very wet ( $P > P_{90}$ ), following modern criteria to establish these classes (García de Pedraza and García Vega, 1989). The values of percentiles are the following:  $P_{10} = -288$  mm;  $P_{25} = -168$  mm;  $P_{75} = 75$  mm and  $P_{90} = 262$  mm. Indexes range from  $+5$  to  $-3$ , so estimated rainfall anomalies  $P_e$  range from  $430$  to  $-370$  mm. Results are shown in Table V. The annual index is obtained by summing seasonal indexes, whose values range from  $+2$  to  $-2$ . The lack of information relating to summer prevents extreme values  $+8$  and  $-8$  being reached. Therefore, an annual index  $I \geq +2$  indicates more than a single wet season, and consequently the year may be classified as wet or very wet. An analogous comment is valid for index values  $I \leq -2$  and dry or very dry years. As can be seen in Table V, results distinguish clearly rainy years, and in minor detail dry years. This is caused by the indexes assignment for hydrological and meteorological droughts. Qualitative information from sources is not very detailed because the simple absence of rainfall (meteorological drought, index value  $I = -1$ ) was recorded promptly, due to its possible impact on agriculture, and hydrological drought requires more time to be detected. The consequence is a slight lack

Table V. Comparison between estimated precipitation ( $P_e$ ) and classification of years according to the percentile distribution of the instrumental series of anomalies (1791–1850)

Index	$P_e$ (mm)	Comparison	Class
+5	430	$P_e > P_{90}$	Very wet
+4	330	$P_e > P_{90}$	Very wet
+3	230	$P_{75} \leq P_e \leq P_{90}$	Wet
+2	130	$P_{75} \leq P_e \leq P_{90}$	Wet
+1	30	$P_{25} \leq P_e < P_{75}$	Normal
0	-70	$P_{25} \leq P_e < P_{75}$	Normal
-1	-130	$P_{25} \leq P_e < P_{75}$	Normal
-2	-270	$P_{10} \leq P_e < P_{25}$	Dry
-3	-370	$P_e < P_{10}$	Very dry

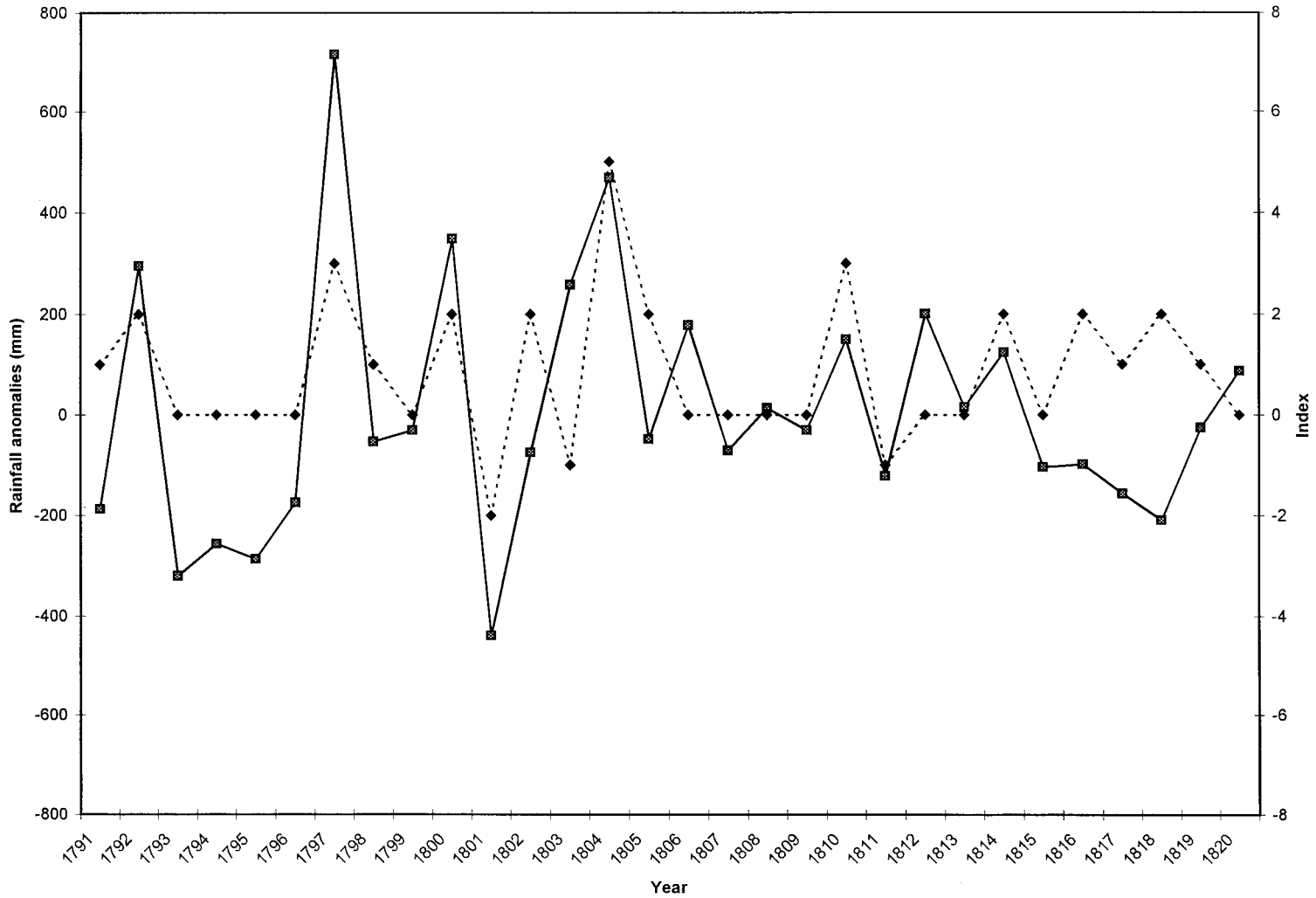


Figure 4. Calibration of the precipitation index, 1791–1820. Continuous line: anomalies of the measured precipitation; dashed line: precipitation index obtained from qualitative records

Table VI. Statistics of the anomalies of measured precipitation ( $P_m$ ), estimated precipitation ( $P_e$ ), and difference  $P_e - P_m$ , in the verification period 1821–1850

Parameter	$P_m$	$P_e$	$P_e - P_m$
Size	30	30	30
Average (mm)	-63.80	1.63	65.43
S.D. (mm)	207	196	192
Variance (mm <sup>2</sup> )	42 807	38 543	36 823

of symmetry in the distribution of values, with greater precision corresponding to intense and/or frequent rainfall.

## 5. VERIFICATION

Verification of climate reconstruction with independent data establishes the reliability of the studied climate for intervals outside the calibration period. The chosen verification period is 1821–1850. The verification process involved applying the obtained linear regression for the calibration period to the indexes corresponding to the verification period. In this way, estimated total annual rainfall anomalies  $P_e$  were obtained and later compared to those measured  $P_m$ . Error margins for estimated rainfall anomalies  $P_e$  were obtained by applying the relation:

$$\Delta P_e = \Delta a + |I| \Delta b$$

where the index value assignment has no mistake. This condition limits error margins, although it allows for assigning a higher confidence level to results in case validation is confirmed. Results can be appreciated in Figure 5. In general, the measured series  $P_m$  and the estimated series  $P_e$  are similar, with similar fluctuations, maxima and minima. In comparing, error intervals have been considered. The main divergence is to be discovered in values corresponding to 1821–1825, 1833 and 1842 (when estimated values, including the error limits, are higher than measured values, that is, the rainfall values are overestimated) and 1838 and 1849, when estimated values, and the error limits, are lower than measured values (rainfall values underestimated). These divergences are a result of two factors; lack of qualitative data, which imposes a 0 value index, as in 1833 and 1838, by means of which drier conditions are overestimated while wetter ones are underestimated, or divergence between the local and regional series, where the measured rainfall anomalies values and the estimated values are different in absolute value, but they display similar behavior and fluctuations. Thus, qualitative reports referring to 1821–1825, 1842 and 1849 do not correspond to Gibraltar, but to different locations in the Guadalquivir Basin (Seville) and the Mediterranean Coast (Málaga). However, the fact that fluctuations are similar confirms the utility of using Gibraltar as a reference station to study fluctuations, as was established in Section 2.

Comparison between the measured and the estimated series was made by resorting to several statistical techniques; Spearman rank correlation,  $t$ -test for difference between means and  $t$ -test for pair comparison. Again, the non-normal character of the series advises nonparametric methods, like Spearman rank correlation. Tests that are insensitive to the form of frequency distribution are termed 'robust'. Some tests that were originally developed on the assumption of a normal distribution turn out to be quite robust when applied to data whose distribution deviates considerably from the Gaussian form. The  $t$ -test is robust, whereby it can validly be applied to data possessing any arbitrary frequency distribution (Mitchell, 1966). In applying this test, the empirical estimation of the mean and the variance was used. According to Sneyers (1990), the empirical mean and variance have the property of being unbiased estimates of the true mean and variance, whatever the shape of the data distribution. Table VI lists the main statistics for both series, together with the difference series. In the  $t$ -test for paired comparison, the null hypothesis establishes that the series difference between values from both samples is a sample of a 0-average

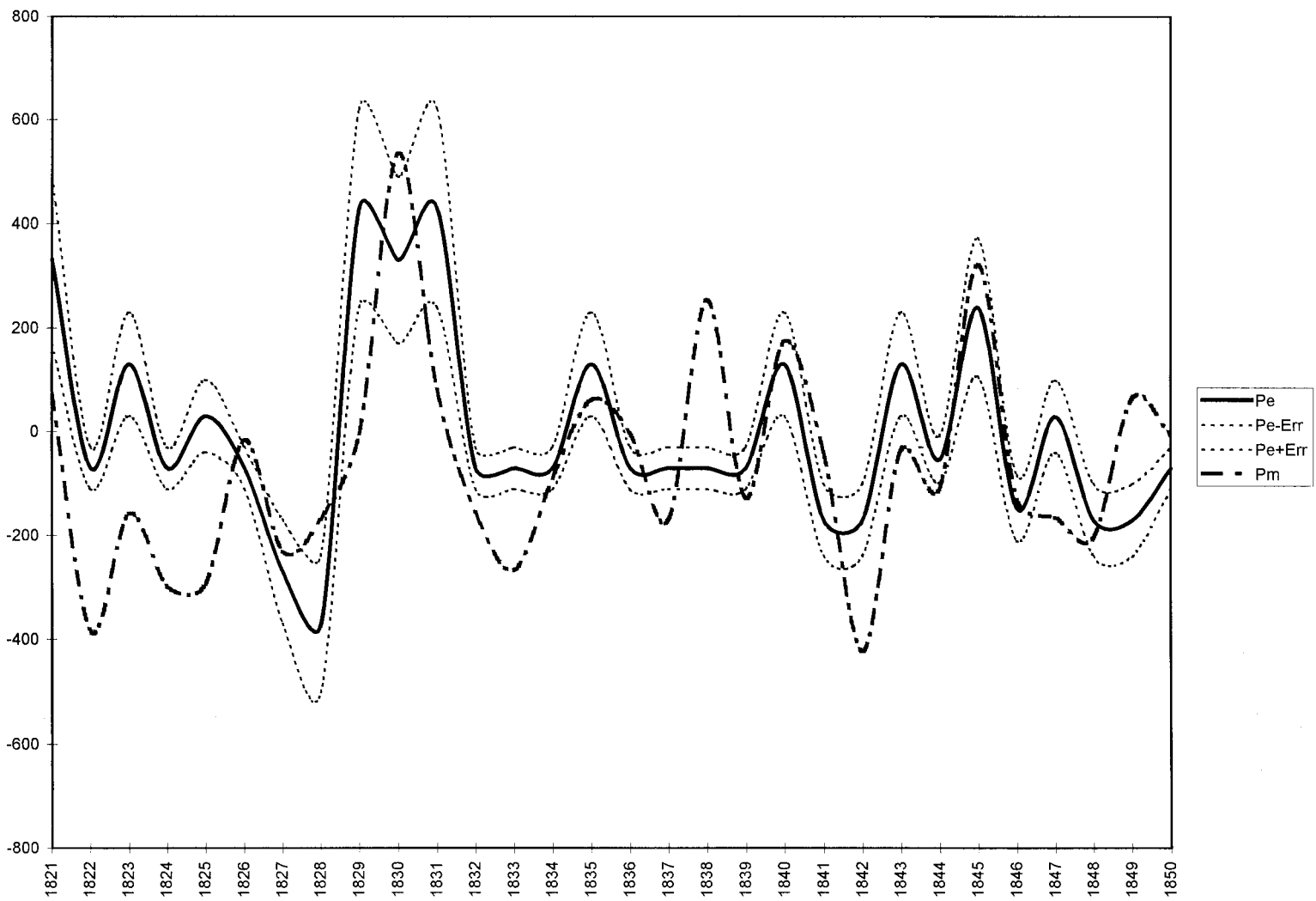


Figure 5. Comparison between measured precipitation  $P_m$  and estimated precipitation  $P_e$ , 1821–1850. Error bands are also shown

population. This means that there is no meaningful difference between the two methods of analysis used to obtain both series.

The results obtained were the following: the Spearman rank correlation coefficient is 0.52; the  $t$ -tests statistics for comparison between means is 1.2565 ( $< t_{0.025; n_1 + n_2 - 2}$ ) and the  $t$ -test statistics for the paired comparison 1.8676 ( $< t_{0.025; n - 1}$ ). They are all statistically significant at the 95% confidence level, indicating that there are no meaningful differences between estimated and measured rainfall anomalies. Finally, the Pearson correlation coefficient was also obtained, in spite of the non-normal character of the series, resulting in a value of 0.55, statistically significant at the 95% confidence level. In conclusion, as can be appreciated in Figure 5, the estimated series reproduces reasonably good rainfall anomaly fluctuations for the verification period.

## 6. RECONSTRUCTION

Once the calibration and validation processes have been fulfilled for the overlapping period, the subsequent step is to apply the obtained regression for the calibration period 1791–1820 to the indexes series corresponding to the pre-instrumental period 1501–1790. In this final step of the reconstruction it must be taken into account that the lack of qualitative data, which produces a 0 value in the system, leads to the overestimation of dry conditions, while underestimating wetter ones for those seasons or years for which information is unavailable. An example of this problem was presented earlier, in the comparison of the estimated and measured anomalies for the verification period; lack of qualitative data, which produces a 0 index value, in 1833 and 1838, leads to overestimated drier conditions and underestimated wetter conditions, respectively. As density of information from the 19th century practically doubles that of preceding centuries (Table IV), this problem must be amplified in considering the pre-instrumental period. Furthermore, while data exists in the instrumental series covering the entire interval between the minimum and the maximum values detected, the reconstruction process assigns a sole estimated value compatible with different values of the instrumental series. As a consequence, the variance of the reconstructed series will be lower than that of the instrumental series.

The obtained regression for the calibration period was applied to the indexes series of the pre-instrumental period. Subsequently, the empirical variance of the estimated series was calculated and compared to the empirical variance of the instrumental series. The results indicated that the variance for the instrumental period (198 years) was 65791 mm<sup>2</sup>, and 28880 mm<sup>2</sup> for the estimated series in the pre-instrumental period (290 years). In a similar problem, a smaller variability in the reconstructed series towards the observed one, was discovered by Fritts *et al.* (1979) in their reconstruction of climate variations from tree rings in USA from 1602 onwards. If the entire series is considered, it is basically a homogeneity problem. Heterogeneity correction in rainfall series is usually carried out using homogeneous series close to the problem series by applying a multiplying factor (Jones *et al.*, 1985). In the present case, there is no homogeneous series to compare with the heterogeneous series. The solution to this problem, as pointed out by Fritts *et al.* (1979), is thus making the reconstruction by multiplying each value by the empirical standard deviation of instrumental data, and dividing it by empirical standard deviation of estimations, i.e. obtaining rainfall anomalies  $P_r$  as:

$$P_r = \frac{S_m}{S_e} P_e$$

where  $P_e$  represents estimated rainfall anomalies by applying the obtained regression during the calibration period;  $S_m$  and  $S_e$  are, respectively, the empirical standard deviation of instrumental and estimated series. In order to check whether the correction resulted in the expected way, the Thom test was applied to the  $P_r$  series, resulting in a statistic value  $Z = 0.083$ , which confirmed the homogeneity null hypothesis at the 99% confidence level. The final result is shown in Figure 6, which represents the 10-year moving averages for rainfall anomalies with regard to the average value of the instrumental period, where instrumental data began from 1791 onwards.

In spite of methodological problems in the moving average, possible spurious cycles and modifications in statistical characteristics from the original series (Sneeyers, 1992), this method allows for the identification of behavioral standards in timescales longer than the chosen step (10 years in this case). It also smoothes the pronounced interannual variability, as a result of extreme nature of the compiled records.

In general, the most relevant aspects of the results can be summarized as follows: after some years of prevailing dry anomalies during the 16th century, with a minimum around 1540, a clear wet period begins at the end of this century extending until mid-17th century. The wetter years correspond to 1590s, 1630s and 1640s. The so-called late Maunder Minimum, a period of a minimum number of sunspots, 1645–1715, is characterized by alternating dry and wet anomalies, with a slight decreasing trend. The 18th century is clearly dry, with a minimum around 1750. At the end of 17th and the beginning of the 19th century, rainfall anomalies are fluctuating, and increase reaching a maximum around 1850. From the late 19th century, a progressive decrease in rainfall takes place, only interrupted by precipitation in the 1960s. These results demonstrate a variability similar to that detected in annual mean temperature for the Northern Hemisphere (Mann *et al.*, 1998): pronounced cold periods during the mid-17th and 19th centuries, and somewhat warmer intervals during the mid-16th and late 18th centuries, with almost all years prior to the 20th century well below the 20th century climatological mean. Therefore, wet (dry) periods in Andalusia may be related to cold (warm) periods in the Northern Hemisphere. These results display a general fluctuating character, with alternating dry and wet periods. Fluctuations occur not only on a decade timescale, but also on an interannual scale. It seems clear that the main phase of the LIA in Andalusia corresponds approximately to the period 1590–1650, when the prevailing anomalies were wet. According to these results, the dry period that began in the 1960s is similar to the driest periods detected in preceding centuries, especially around 1540 and 1750. The comprehensive analysis, from a statistical point of view, of the obtained series can clarify rainfall evolution during the entire period under study. This analysis will enable the characterization and detection of climatic change (increasing or decreasing trends, abrupt changes, periodicities) and, consequently, comparing weather evolution in pre-instrumental and instrumental periods. Consequently, it will be possible to compare climate evolution when anthropogenic factors are present (instrumental period) or absent (pre-instrumental period). This task, now under

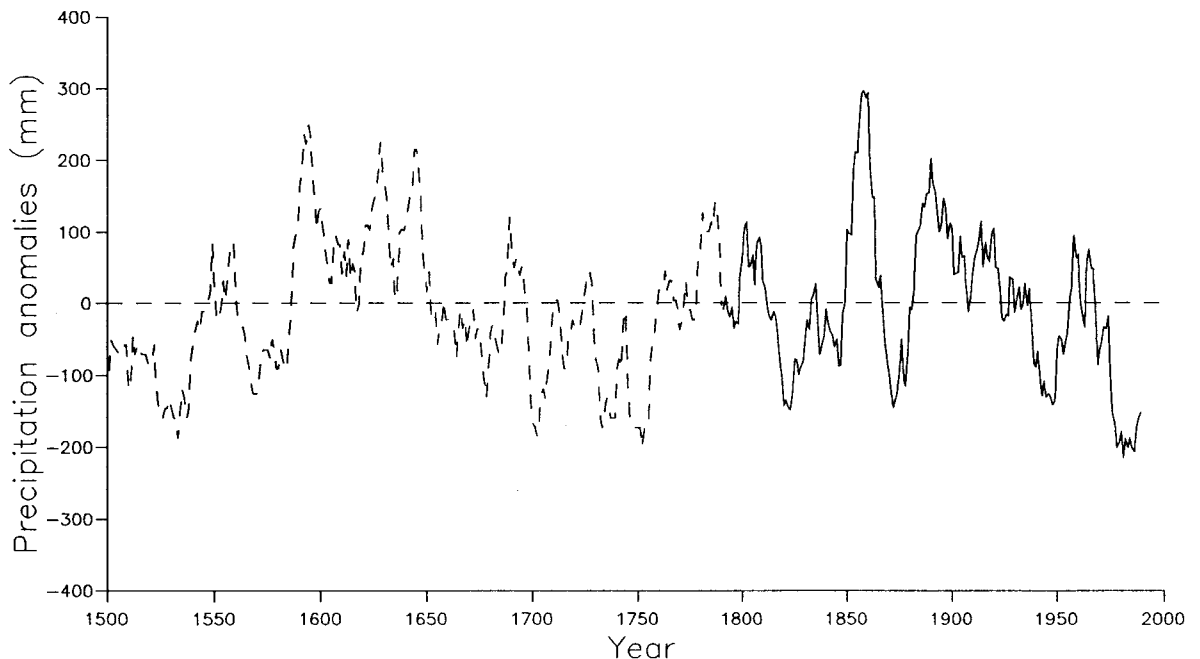


Figure 6. Reconstruction of precipitation anomalies 1501–1990, 10 years moving average (dashed line: historical precipitation reconstructed; continuous line: instrumental data from 1791 onwards)

preparation, must be fulfilled with the study of rainfall seasonal evolution, which will provide the means for perfecting the analysis from the atmospheric dynamics approach.

In this sense, the analysis of weather types responsible for extreme phenomena can help to interpret the dynamic behavior of the atmosphere during the entire period. Most of floods in the Guadalquivir Basin are associated with persistent rainfall caused by Atlantic lows and their related fronts crossing the region from west to east. These situations are more common in winter, although they can also be detected in autumn and spring (Castillo Requena, 1989). They are a consequence of the southwards shift of isobaric systems caused by the expansion of the circumpolar vortex. In summer, local storms and convective rainfall may occur (Capel Molina, 1977). On the other hand, dry periods in the Iberian Peninsula are caused by the evolution of subtropical pressure belts (Font Tullot, 1989). If high pressure centers are intensified in autumn, a cold anticyclone center might evolve over the Iberian Peninsula, lasting all through the winter. The Azores High can also be delayed in its southwards winter shift invading the Iberian Peninsula and leading to droughts which might last through the spring heating (Capel Molina, 1975). In short, prevailing droughts can be associated with hemispheric zonal circulation, whereas periods of intense rainfall can be associated with hemispheric meridional circulation. The sign of anomalies during the studied period can indicate the prevalence of one type of circulation or the other one. Therefore, positive anomalies would indicate prevailing meridional circulation, and negative anomalies would indicate prevailing zonal circulation.

Limits on the database compels careful consideration of these results. Obviously, it is necessary to enlarge the database in order to obtain a finer picture of past rainfall evolution. Such enlargement will allow the perfection of the timescale of the analysis as well as the reconstruction reliability. Besides, comparison with similar studies applied to other Iberian and European regions will enable a deeper understanding of time–space variability in weather events, and, consequently, in climatic change phenomena.

#### ACKNOWLEDGEMENTS

This work has been carried out under the Research Projects CLI95-1928-CO2-01 (CICYT) and CLI98-0930-CO2-01 (CICYT), Spanish Interministerial Commission for Science and Technology. Instrumental data were contributed by the Spanish National Meteorological Institute (INM). The authors wish to thank J.F. Esteban-Parra for the English version of this paper

#### APPENDIX A. DATA SOURCES

A complete description of the data sources would excessively enlarge the length of this work. So the authors have preferred to present them in this Appendix in a brief manner. A more detailed study may be found in Rodrigo (1994) and in the additional bibliographic references. The schema is as follows:

CODE. Title in English.

Original title (year of publication), author (dates of birth and death, if they are known).

Additional bibliographic references.

UA-1. *Annals of Granada*.

*Anales de Granada*, F. Henríquez de Jorquera (1594–1646).

Marín Ocete, A., ed., 1934. Universidad de Granada, Granada.

UA-2. *Accounts of Seville*.

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UA-4. *Annals of... Seville.*

*Anales de la Real Plaza de Toros de Sevilla 1730–1835* (1917), R. de Rojas y Solís.

Property of the Library of Andalusia.

UA-5. *Annals of... Seville.*

*Anales Eclesiásticos y Seglares de la Ciudad de Sevilla* (1747), L. Baptista de Zúñiga.

Property of the University of Granada Library.

UA-6. *Historical comments of Málaga.*

*Conversaciones históricas malagueñas* (1792), C. García de la Leña.

Property of the University of Granada Library.

CH-1. *History of Cádiz.*

*Historia de la Ciudad de Cádiz* (1598), A. Orozco (?–1599?).

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CH-2. *Accounts from the city of Utrera.*

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Menéndez Pelayo, M., ed., 1883. *Obras de Rodrigo Caro*, Sociedad de Bibliófilos Andaluces, Sevilla.

CH-3. *Antiquity and Excellence of Granada.*

*Antigüedad y Excelencias de Granada* (1608), F. Bermúdez de Pedraza (1585–1655).

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CH-4. *History of Jaén.*

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CH-8. *History of Gibraltar.*

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CH-9. *History of Granada.*

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GH-2. *Continuation of the General History of Spain.*

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GH-3. *Comments of Spanish War and the king Felipe V.*

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RH-2. *Ecclesiastical History of Granada.*

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RH-5. *History of the College of San Pablo.*

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RH-6. *Bishops of Granada.*

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R-4. *Huracan in Granada.*

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R-5. *Gazette of Granada.*

*Mamotreto de la Gazetilla curiosa o Semanero Granadino*. (1764–1765)

Property of the Library of Andalusia.

R-6. *Letters of the Jesuits.*

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R-7. *Economical Newspaper of Granada.*

*Mensajero Económico y Erudito de Granada*. (1796–1797).

Property of the University of Granada Library.

R-8. *Weekly of Málaga.*

*Semanario erudito y curioso de Málaga*. (1797, 1799, 1800).

Property of the University of Granada Library.

R-9. *Weekly of Granada.*

*Samanario de Granada*. (1800).

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R-10. *Gazette of Granada.*

*Gazeta de Granada* (1813).

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