Theor. Appl. Climatol. 52, 207–218 (1995)

Theoretical and Applied Climatology



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# Reconstruction of Total Annual Rainfall in Andalusia (Southern Spain) During the 16th and 17th Centuries from Documentary Sources

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With 6 Figures

Received October 12, 1994
Revised April 28, 1995

**Summary**

This study describes a reconstruction of rainfall characteristics in Southern Spain from 1501 to 1700 AD, during the beginning of the period called the 'Little Ice Age'. Weather information was taken from original documentary sources (urban annals, local and religious histories, municipal documents, relations, etc.) in the region. A numerical index was established to characterize the rainfall, its characteristics, evolution and geographical distribution. Results were characteristics compared with modern precipitation data and with the results of other studies of historical climate. The general conclusion is that rainfall in Western Andalusia increased from approximately 1550 to 1650 AD. Some perspectives for future research work are outlined.

## 1. Introduction

Anthropogenic influences on climate are superimposed on a background of natural climatic variability which may be attenuated or enhanced. Palaeoclimatic studies help in understanding the nature and possible causes of the present climatic variations. They allow us to analyse the relatively short instrumental record of climate variability on longer time scales (Berger et al., 1989).

The last 500 years was a period of complex climatic anomalies. Although there is no evidence for a worldwide synchronous and prolonged cold interval (Jones and Bradley, 1992), the so-called 'Little Ice Age' period (LIA) provides the best opportunity of investigating the possible mechanisms affecting climate on the decade to century time-scales. The LIA was the most significant period of glacial development in historical times (the last 2000 years), and its study, therefore, may yield a better understanding of natural climate fluctuations. Moreover, there are many proxy data for this period that are precisely dated and with good temporal resolution (Pfister, 1994). Among these, documentary data deserve special attention. In general, these data record climate anomalies and extreme events, such as droughts and floods, allowing us to relate such events to climatic changes on the decade to century time scales.

Research into climate history in Spain and particularly Andalusia in general has received little attention from specialists, and the few works under-taken (Fontana Tarrats, 1977; Mackay, 1981; Alvarez Vázquez, 1986; Font Tullot, 1988) are largely qualitative descriptions without a quantitative basis. In addition, some of these works (for example, Fontana Tarrats, 1977) have inaccuracies regarding the analysis of the data sources and their reliability, as well as the spatio-temporal distribution of the data. This work focusses on the analysis of rainfall in Andalusia during the 16th and 17th centuries, when the onset of the LIA has been recognised as having occurred (Lamb, 1977; Font Tullot, 1988). The climatic interest of this region is due to its geographical position and latitude (around 37 °N). The region is influenced by the flows from the Atlantic Ocean and the Mediterranean Sea. Rainfall distribution through the year is dominated by the Azores High, with dry summers and irregular precipitation in the other seasons of the year. In this region most climatological perturbations are associated with the behavior of the polar jet. Given the importance of the polar jet stream dynamics for climate, study of this region is very interesting.

In our earlier work (Rodrigo et al., 1995) we have inferred from the analysis of historical sources that the onset of the LIA in Andalusia occurred approximately in the mid 16th century. The LIA was characterized by wet conditions, which lasted at least until the mid 17th century. This result agrees with other analyses of historical climate in Mediterranean latitudes (Creus Novau and Puigdefábregas Tomás, 1984; Barriendos, 1994). However, in that work we did not obtain quantitative reconstructions of rainfall changes to allow a direct comparison with the present meteorological conditions. A first approximation to this problem was made in Rodrigo et al. (1994), limiting the study to Seville and Granada cities, and to the 1601–1650 AD period. The aim of this work is to enlarge the spatio-temporal coverage of this reconstruction by analysing the whole region and the 200 year period when the main phase of the LIA occurred (16th and 17th centuries). The objective is to consider this period in relation to the "normal" climate in the 20th century.

The following section briefly describes the data sources used in the study. The method of analysing and reconstructing rainfall records is described in Section 3, and the comparison with other proxy data (such as tree rings) is discussed in Section 4. Finally, some preliminary conclusions and perspectives for the future are outlined.

## 2. Data Sources

Historical meteorological records have been obtained by critical analysis of original documents, each of them originating from a specific tipology: urban annals (UA), city histories (CH), general histories of Spain (GH), religious histories (RH), brief relations of events of journeys and letters (R), and municipal and ecclesiastic archive books (A). The advantage of using different kinds of sources is that the objectives of the authors and the character of the texts vary from one kind to another. This feature allows an adequate cross-comparison of the events reported, and avoids to a certain degree the subjectivity of the authors (Ingram et al., 1981).

The criteria used for reliability here are the principles of contemporaneity, propinquity, faithful transmission, cross-comparison of information from different sources, and a good agreement with other proxy data, such as, the agricultural yields (wheat and wine). Another reliability criterion is the accuracy of the authors when describing nonmeteorological events, such as, for example, military and political occurrences, plagues, famines, known astronomic events, etc. Table 1 lists the sources we

Table 1. *Time Coverage of the Data Sources. < Indicates Information Previous to the corresponding year, Analogous for >, but for Later Information than this year.* The source code are indicated in the Appendix

| Source | 16th Century | 17th century |
|---|---|---|
| UA-1 | 1588, 1590 | 1603 to 1646 |
| UA-2 | 1600 | 1601 to 1678<br>1680, 1684<br>1691, 1692 |
| UA-3 | 1501 to 1600 | 1601 to 1700 |
| CH-1 | < 1598 | |
| CH-2 | < 1600 | |
| CH-3 | < 1600 | |
| CH-4 | | < 1628 |
| GH-1 | 1501 to 1600 | 1601 to 1621 |
| GH-2 | 1516 to 1600 | |
| RH-1 | | 1604 to 1605 |
| RH-2 | 1501 to 1600 | 1601 to 1633 |
| RH-3 | 1583 to 1600 | 1601 to 1681 |
| R-1 | 1561 to 1569 | |
| R-2 | 1554, 1560, 1576<br>1582, 1585, 1586<br>1588, 1589, 1590<br>1599, 1600 | 1602, 1608, 1610<br>1617, 1656, 1668 |
| R-3 | | 1604, 1618, 1626<br>1628, 1629, 1636<br>1651, 1653, 1661<br>1671, 1680, 1681<br>1684 |
| R-4 | | 1629 |
| A-1 | 1501 to 1600 | |
| A-2 | 1522, 1557, 1566 | 1604, 1614, 1618 |
| A-3 | > 1560 | |
| A-4 | < 1575 | |
| A-5 | 1501 to 1600 | 1601 to 1700 |

Table 2. *Number of Sources and Types of Sources for each fifty Years Period from 1501 to 1700*

| Period | Sources | Types of sources |
|---|---|---|
| 1501–1550 | 14 | 5 |
| 1551–1600 | 20 | 6 |
| 1601–1650 | 16 | 6 |
| 1651–1700 | 9 | 5 |

have used, identified by the code assigned in the Appendix 1 at the end of this work, showing the years or periods covered by each of them. A more detailed description of each source may be found in Rodrigo (1994) and Rodrigo et al. (1994).

Authors of the chronicles were priests, lawyers and merchants with similar cultural backgrounds. They were eyewitnesses to the events, or they recorded their information from oral and written sources. They all lived in Andalusian cities and were similar with the 'normal' behaviour of Andalusian climate. For the greater part of the period considered here there are generally several sources of different kinds available for each year. In Table 2 the number of sources and types of sources are accounted for, for each fifty-year period within the total period of study.

In conclusion we can affirm that we have obtained a homogeneous data set for climatic conditions in Andalusia during the period of study, given the similar cultural background of the authors, and the character of the sources (Ingram et al., 1981; Baron, 1992). Of course, the study we present here is not exhaustive. There are still many unexplored sources for palaeoclimatic studies. However, with these records we are able to analyse the evolution of the major rainfall anomalies that affected Andalusia in the period of study and therefore draw certain conclusions about Andalusian climate during the LIA.

## 3. Data Analysis

### 3.1 *Character of the Data*

The data recorded are qualitative descriptions that for the greater part, but not always, deal with natural hazards and events that had a direct impact on the society of the period. Although in other parts of Europe documentary sources may provide information on 'normal' events (Ogilvie, 1992), this is not true in Andalusia, documents such as meteorological diaries do not exist (as opposed to, for instance, in Paris between 1675 and 1715 by Louis Morin (Pfister and Bareiss, 1994). Generally, the data correspond to extreme events, the greater part relating to agricultural yields, drying of rivers and springs, lack of rain, storms, dry and wet spells, floods, etc. The reconstruction of mean values of meterological variables from extreme events has been made in other works on climate history (Shaowu and Zongci, 1981; Shaowu, 1991). The basic assumption here is that the extreme events are more sensitive to climate variability than average climate and therefore variations in the frequency and intensity of extreme events are the main features of the changes in average climate (Katz and Brown, 1992).

### 3.2 *Geographical Precision*

Most of the records are from different cities in the region, such as Seville, Córdoba, Málaga and Granada (Fig. 1). In the period of study, the influence of meteorological factors on agriculture was very strong due to its rudimentary structure and methods. In consequence, the authors focused their attention on the different events that could damage harvests. Therefore, we may distinguish the reports related to agriculture which are associated with the city and its supply area (droughts, intense and continuous rains). In addition, we have reports on local conditions such as summer storms, and generalized records, in which the authors describe conditions in broader areas, including relationships of trips between different cities in the region.

We used certain cities as representative of the regional climate (as in Rodrigo et al. (1994) with Seville and Granada), in a similar way to the modern uses of meteorological seasons. However, for the period we want to study here, we would obtain very heterogeneous records, with different periods covered, different lengths for each period, and many gaps. The alternative method we have used is to associate each record to the appropriate climatic region within Andalusia. We have to establish a climatic division of the region, and therefore it is necessary to have in mind the modern climatological patterns.

On the basis of rainfall we can distinguish in Andalusia two well-defined zones: Western Andalusia, which embraces the low lands of the Guadalquivir River Basin and the Atlantic coast; and Eastern Andalusia, which embraces the In-

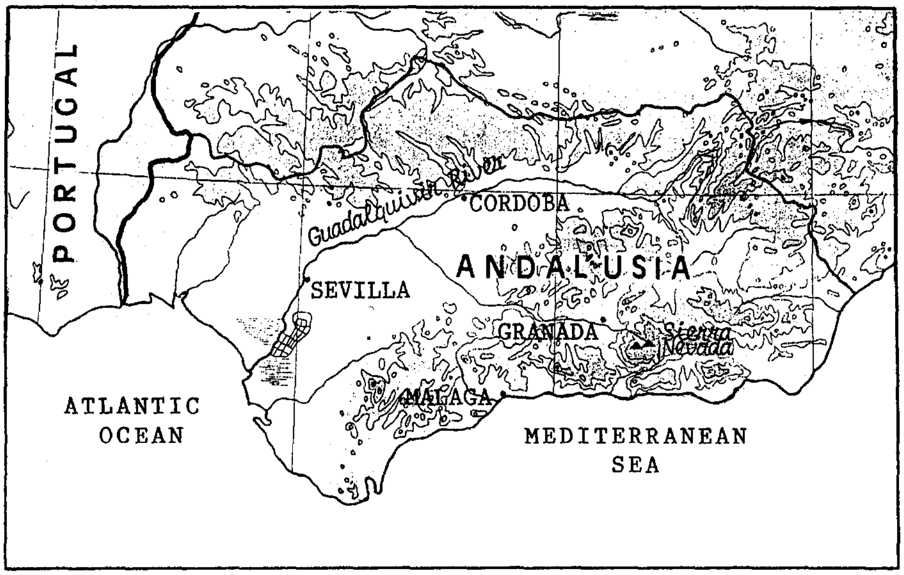


Fig. 1. Map of the studied region

Table 3. *Number of Months, Seasons and Years with Climatic Records in Western and Eastern Andalusia. In Parenthesis, the Percentage with Respect to the Total Number Possible in the Study Period*

| | Western Andalusia | Eastern Andalusia |
|---|---|---|
| January | 39 (19.5%) | 21 (10.5%) |
| February | 29 (14.5%) | 12 (6.0%) |
| March | 35 (17.5%) | 9 (4.5%) |
| April | 33 (16.5%) | 16 (8.0%) |
| May | 28 (14.0%) | 15 (7.5%) |
| June | 16 (8.0%) | 15 (7.5%) |
| July | 6 (3.0%) | 7 (3.5%) |
| August | 7 (3.5%) | 9 (4.5%) |
| September | 7 (3.5%) | 11 (5.5%) |
| October | 10 (5.0%) | 6 (3.0%) |
| November | 13 (6.5%) | 6 (3.0%) |
| December | 15 (7.5%) | 13 (6.5%) |
| Total months | 236 (9.8%) | 142 (5.9%) |
| Winter | 67 (33.5%) | 40 (20.0%) |
| Spring | 60 (30.0%) | 31 (15.5%) |
| Summer | 27 (13.5%) | 27 (13.5%) |
| Autumn | 35 (17.5%) | 24 (12.0%) |
| Total seasons | 189 (23.6%) | 122 (15.2%) |
| Total years | 155 (77.5%) | 102 (51.0%) |

trabaetic depressions near the Sierra Nevada mountains and the Mediterranean coast (Capel Molina, 1977; Castillo Requena, 1989). In Western Andalusia the influence of the Atlantic flow is dominant, whilst Eastern Andalusia is characterized by a reduced effect from ocean mechanisms and a stronger influence from Mediterranean mechanisms. An analysis of the climatic behaviour in these two zones, oriented along a west-east axis, could therefore identify on the spatial distribution of the climatic events and the influence of mesoscale forcing factors, such as topography or proximity to the sea.

### 3.3 Temporal Precision

We have found a wide range of time scales in the records: from one day (even the hour of the day for instance, storms, hail, floods events) to one year, including references to months and seasons of the year (droughts, wet spells). In Table 3 we show the number of months, seasons and years with rainfall information for the two zones considered. Less than the 10% of the total number of months may be characterized from a meteorological point of view. The months with more records are January, March and April. The percentage increases if we consider the number of seasons (23.6% in Western Andalusia, 15.2% in Eastern Andalusia), with the predominance of winter and spring. Finally, if we consider the number of years, the percentage is the 77.5% for Western Andalusia and the 51% for Eastern Andalusia.

The extreme events recorded show a density of 2.3 items per year for Western Andalusia and 1.7 items per year for Eastern Andalusia. For the 16th century, the density is 1.9 items/year and 0.6 items/year for Western and Eastern Andalusia, respectively. For the 17th century the density is slightly higher, 2.6 items/year for Western and 2.1 items/year for Eastern Andalusia. In the above mentioned work (Rodrigo et al., 1995), we discussed the possibility of a statistical analysis using these frequencies of recorded events. The conclusion was that, given the temporal distribution and the extreme character of the records, the appropriate time unit is one year. In consequence, the climate variable one we are interested in reconstructing is total annual precipitation.

### *3.4 Annual Rainfall Index*

Rainfall records were classified in 5 categories on a scale from −2 to +2. For cases in which the authors did not comment on weather conditions and where other non-meteorological events are found, we considered the situation 'normal' and we assign the index 0. The index −2 was given to records of droughts accompanied by drying of rivers and springs. As an example of this type of record we can quote the reference to the drought in the winter and spring of 1605 (source UA-1, page 540) given in the Appendix 2, paragraph 1, at the end of this work. This text provides the general characteristics of the worst droughts: lack of rain, sowing impossible or very bad harvests, rise of prices, drying of rivers and springs, lack of pasture and death of cattle.

Records of meterological drought, that is, lack of rain without the explicit mention of deficits in the runoff of rivers and springs, are assigned to index −1. In the books of act of the City Chapter of Granada (source A-2) is recorded on 12 March 1521 an example of this situation given in the Appendix 2, paragraph 2, where it is shown that the lack of rain in winter is recorded together with municipal orders to use in an appropriate way the water of rivers and springs. Continuous and strong rains and rainly periods are assigned the value + 1. For instance, the source UA-3 (pp. 387, Vol. 3) describes the strong and continuous rainfall during autumn 1543 indicating damages to the city buildings and agriculture (Appendix 2, paragraph 3). Finally, rains accompanied by foods were given a value of + 2, as, for example, the description of the flood in Seville, on 25 January 1626, according the source UA-2 (pp 51–54): heavy rainfalls began on 17 January, the river over flowed its banks on 22 January, rainfall continued and on 25 January the city was flooded (Appendix 2, paragraph 4).

These numerical values were assigned to each site and, when it was possible, to each month within the two zones considered. The regional monthly index was obtained by averaging the monthly values corresponding to each site within the zone considered. Afterwards, an index was established for each season of the year considering the number of months with records. Finally, the annual index was obtained in a similar way, by averaging according to the number of seasons of the year and the number of sites with records. This type of index, according to Ingram et al. (1981), tolerates gaps in the records and possible uncertainty in perception and/or actual frequency of the anomalies.

Figures 2 and 3 show the annual time series of the index during the period studied for Western and Eastern Andalusia, respectively. In general, there is high interannual variability in both series, in accordance with the anomalous nature of the

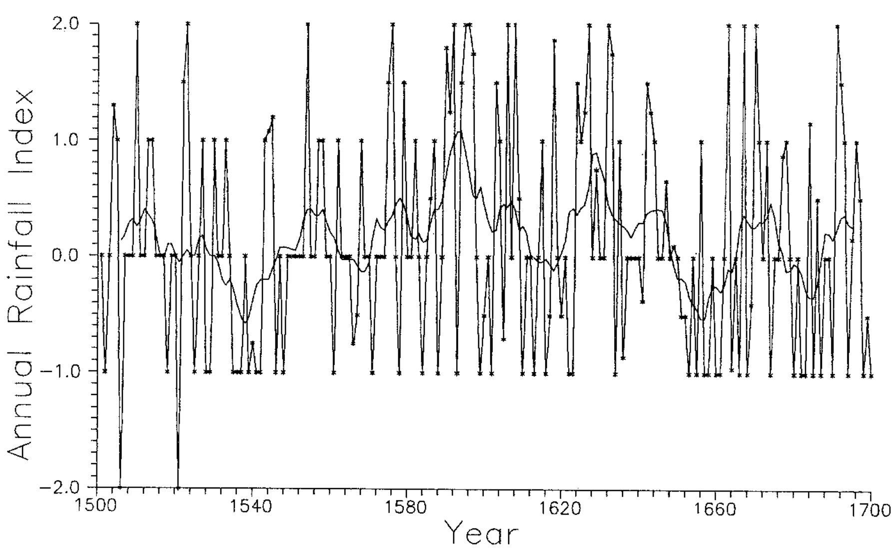


Fig. 2. Time series of the annual rainfall index and 10 years moving average for Western Andalusia in the period 1501–1700 A. D

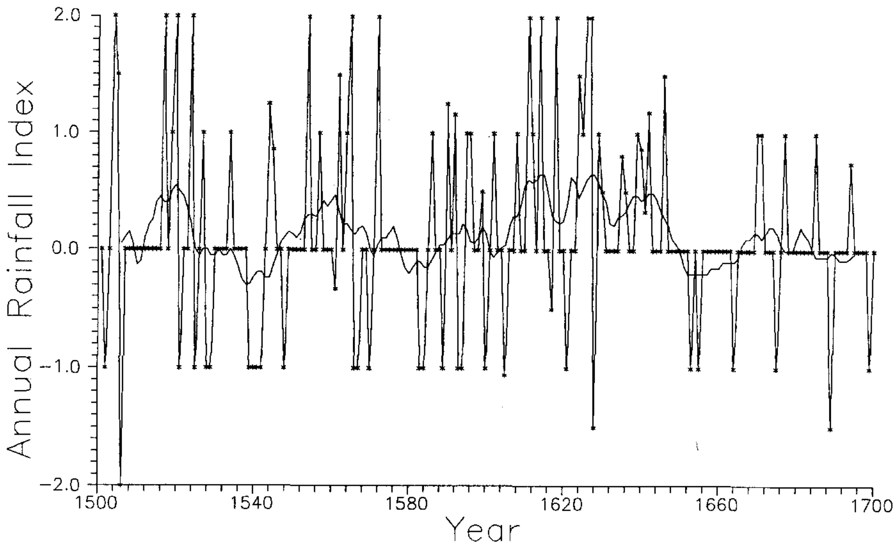


Fig. 3. Time series of the annual rainfall index and 10 years moving average for Eastern Andalusia in the period 1501–1700 A. D

Table 4. *Statistical Characteristics of the Rainfall Index for Western and Eastern Andalusia*

| Parameter | Western Andalusia | Eastern Andalusia |
|---|---|---|
| Average | 0.14 | 0.13 |
| Median | 0 | 0 |
| Mode | 0 | 0 |
| Standard deviation | 0.96 | 0.76 |
| Typical error | 0.07 | 0.05 |
| First quartile | −0.75 | 0 |
| Third quartile | 1 | 0 |
| Interquartile range | 1.75 | 0 |

phenomena recorded. The index, therefore, is interpreted as a measure of the bahaviour of meteorological anomalies in the studied period. Ten year moving averages are also shown in both Figures. Despite the problems of running means (Mitchell, 1966), this is a practical method for smoothing time series and identifying cyclic patterns (Camuffo, 1984). A fluctuating behaviour is observed, in the two series, with wet periods alternating with dry periods. The predominance of wet period is also noticeable, with maxima around the 1590s and 1630s. Dry periods reflect the severe droughts that affected Andalusia in the 1540s, 1650s, and 1680s decades.

Table 4 shows the statistical characteristics of the index for both areas. If we use the average value and the standard deviation as indicators, we find a slight trend of more wet than normal (average value positive) and lesser variability in Eastern Andalusia than in Western Andalusia. The values of the median and the mode provide information on the 'normal' behaviour of rainfall. The value obtained (0) shows that the index, which assigned this value to normal conditions, is appropriate. The interquartile range is a useful measure of the dispersion of the data and their variability, because it considers 50% of the observations and rejects the individual observations near the extremes. In Eastern Andalusia this parameter is 0, and in Western Andalusia it is 1.75, which suggests greater variability of rainfall in Western Andalusia. Given the characteristics of these data; the positive values of the average and the interquartile range values, it would suggest the predominance of wet anomalies over dry anonalies in both zones.

### 3.5 *Reconstruction of the Rainfall*

To reconstruct the rainfall regime in the historical period, a modern meteorological station must be selected for each historical series for reference (Schüle and Pfister, 1992). This station must be respresentative of the climatic conditions in its region. The stations we have chosen are Tablada (Seville) for Western Andalusia and Armilla (Granada) for Eastern Andalusia. Modern data of total annual rainfall in mm correspond to the period 1871–1983 for Tablada, and 1941–1985 for Armilla.

To establish numerical values for rainfall in the historical period, we derived a linear regression model between the index values taken from modern measuring instruments and modern values for rainfall, with the aim of reconstructing the historical values by divergence from modern ones

(Pfister, 1988). First, we established the modern values of the index taking into account the percentiles of the annual rainfall value, according to the following criteria:

If $P(t) < P_{10}$ then $I(t) = -2$
If $P_{10} \leqslant P(t) < P_{25}$ then $I(t) = -1$
If $P_{25} \leqslant P(t) < P_{75}$ then $I(t) = 0$
If $P_{75} \leqslant P(t) \leqslant P_{90}$ then $I(t) = +1$
If $P(t) > P_{90}$ then $I(t) = +2$

where $P(t)$ is the annual precipitation value for the year $t$, and $P_i$ indicates the ith percentile. This classification corresponds to the criteria currently followed to characterize very dry, dry, normal, rainy and very rainy years (García de Pedraza and García Vega, 1989). The drier period in the 20th century was 1934–1954 with 296 mm in Seville in 1954, and 231 mm in Granada in 1953, years with index $-2$ ($P_{10} = 343$ mm in Seville, $P_{10} = 292$ mm in Granada). The wettest period corresponds to 1955–1966, with 1007 mm in 1960 in Seville ($P_{90} = 807$ mm), and 629 mm in 1963 in Granada ($P_{90} = 510$ mm). The following step is to establish a linear regression with $P(t)$ as the dependent variable and $I(t)$ as the independent variable. The results of the linear correlation (95% confidence level) can be seen in Table 5. The correlation coefficients are very high in both cases, indicating the regression equations simulate the data accurately.

Since these correlations were based on the modern data, it is necessary to examine the influence of modern data in more detail before the results can be used. Potentially, the regression equations based on a longer data series and those based on a shorter series may be different. It addition, two data series of the same length but for different periods may also result in different regression relationships. It is necessary to check whether the data length and the selection of data affect the reconstructions (Wang and Zhang, 1992). For this purpose we have divided the Tablada series in two subsections and established regression equations for each one, using the same procedure.

Both two subseries have the same length, one covers the period 1871–1927 and the other covers the period 1928–1983. The method used to assign indices has been applied independently for each subseries, from their percentile distribution. Comparison of the two subseries the influence of the chosen period, and from the comparison with the results of the complete series we obtain the influence of the length of the series. The results are shown in Table 6. Correlation coefficients are very high for both subseries; thus, the regression equations simulate the data correctly. The values of the intercept and the slope are similar, and similar to those calibrated with the complete series. The standard errors are higher than in the complete series because the sample size is lower in both subseries. In conclusion, the selected period and the length of the series do not significantly affect the results.

From the indices established for the historical period the regression equations provide rainfall

Table 5. *Regression Analysis Between the Total Annual Rainfall and the Pluviometric Index Assigned for the Period 1871–1983 for Tablada (Seville) and 1941–1985 for Armilla (Granada) (Confidence level 95%)*

| Western Andalusia | | |
|---|---|---|
| Parameter | Value | Typical error |
| Correlation coef. | 0.94 | |
| Intercept (mm) | 561.14 | 5.53 |
| Slope (mm) | 159.86 | 5.28 |
| **Eastern Andalusia** | | |
| Parameter | Value | Typical error |
| Correlation coef. | 0.94 | |
| Intercept (mm) | 396.31 | 4.63 |
| Slope (mm) | 81.13 | 4.53 |

Table 6. *Regression Analysis Between the Total Annual Rainfall and the Pluviometric Index Assigned for Tablada (Seville) for the Periods 1871–1927 and 1928–1983* (Confidence level of 95%)

| 1871–1927 | | |
|---|---|---|
| Parameter | Value | Typical error |
| Correlation coef. | 0.93 | |
| Intercept (mm) | 550.07 | 8.40 |
| Slope (mm) | 162.15 | 8.33 |
| **1928–1983** | | |
| Parameter | Value | Typical error |
| Correlation coef. | 0.93 | |
| Intercept (mm) | 572.40 | 8.66 |
| Slope (mm) | 161.50 | 8.37 |

Table 7. *Statistical Analysis of the Rainfall Reconstructed for 1501–1700 in Western and Eastern Andalusia and Comparison with Modern Data*

| Parameter | Western Historical | Andalusia Modern | Eastern Historical | Andalusia Modern |
|---|---|---|---|---|
| Average | 584 | 561 | 407 | 398 |
| Median | 561 | 549 | 396 | 391 |
| Mode | 561 | 546 | 396 | 391 |
| St. deviation | 153 | 178 | 62 | 89 |
| St. error | 11 | 17 | 4 | 13 |
| Minimum | 241 | 159 | 234 | 227 |
| Maximum | 881 | 1063 | 559 | 629 |
| Range | 639 | 904 | 324 | 402 |
| $P_{25}$ | 441 | 438 | 396 | 344 |
| $P_{75}$ | 721 | 657 | 396 | 459 |
| $P_{75}-P_{25}$ | 280 | 219 | 0 | 115 |

estimates. The next step is to calculate the basic statistics for the reconstructed series, and to compare these with the modern series (Table 7). The parameters which provide the estimate of the main tendency are the mean value, the median and the mode. According to Stringer (1972) we can consider the values included in the $(P-\sigma, P+\sigma)$ interval as normal, where $P$ is the mean value and $\sigma$ the standard deviation of the modern series. The results listed in Table 7 indicate a normal behaviour with regards to the present, with a slightly wetter trend than the present for both areas.

With regards to the variability of the data, the method of reconstruction does not allow a comparison between the modern and historical data. For the historical period only one precipitation value is assigned to an entire interval between the deciles of the instrumental series. The method rejects values in the historical period, and reduces the variability. Therefore the historical minimum is higher than the modern one, and the historical maximum is lower than the modern one. This problem is partially avoided if we consider the interquartile range. This parameter indicates the main tendency and provides information on the central 50% of the observations. We find a historical interquartile range higher than the modern one for Western Andalusia, the first quartiles being similar, and the third historical quartile higher than the modern one. This indicates wetter conditions than the present in Western Andalusia. For Eastern Andalusia, the behaviour is similar to the modern situation.

Seville is situated practically at sea level and is exposed to the influence of the Atlantic Ocean while Granada is situated at 685 m a.s.l. at the foot of the Sierra Nevada mountains. Due to its easterly position, the influence from the Atlantic is less in Eastern Andalusia and the total annual rainfall in Granada is lower than in Seville. The trend towards wetter conditions for Western Andalusia and normal conditions for Eastern Andalusia, therefore, suggests the important role of the Atlantic synoptic types as a climatic factor in the studied period.

The behaviour of the historical series with regards to the instrumental series is shown in Fig. 4 and 5, for Western and Eastern Andalusia, respectively, where the 10 year moving averages of the historical precipitation (in mm) are expressed as departures from the median of the modern data. We have chosen the median as central value for the instrumental data because this is statistic more reliable than the average value to represent the central characteristics in subtropical and Mediterranean areas (Katz and Glantz, 1977). For Eastern Andalusia the major anomalies in the historical period represent the 18% of the total annual rainfall, while for Western Andalusia they are the 36%. In the two

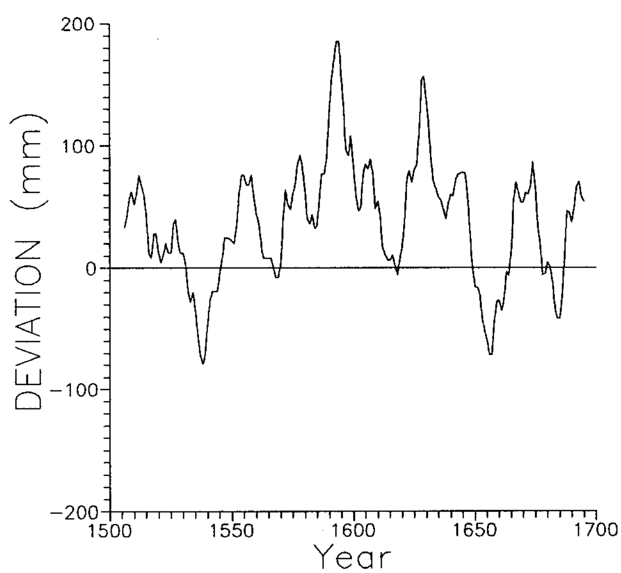


Fig. 4. Precipitation estimates for Western Andalusia (10 years moving average) expressed as departures from the median for 1871–1983

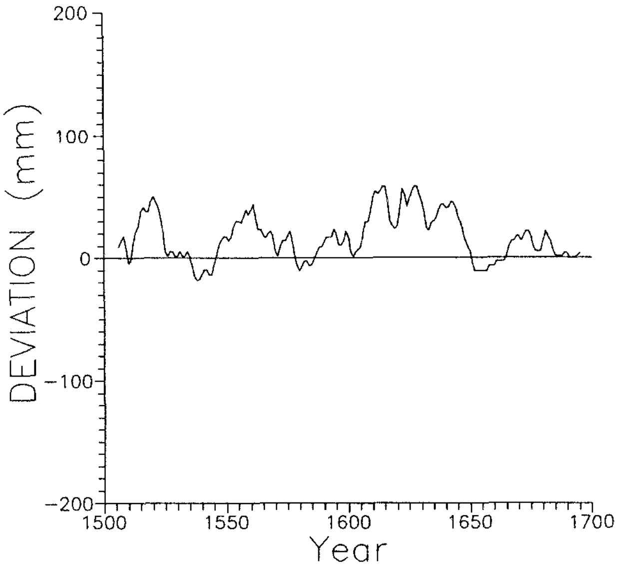


Fig. 5. Precipitation estimates for Eastern Andalusia (10 years moving average) expressed as departures from the median for 1941–1985

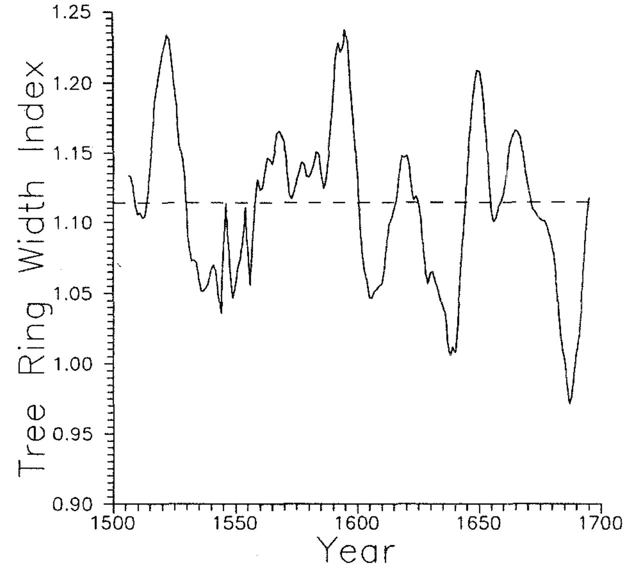


Fig. 6. Tree ring width index (10 years movoing average) of 'Pinus Nigra Arnold' in Sierra de Cazorla mountains (data from Creus Novau and Puigdefábregas Tomás, 1984). The dashed line indicates the average value for the 1500–1700 period

regions the predominance of the wet anomalies is observed between the mid-16th century and mid-17th century. These results are in accordance with those for the entire region (Rodrigo et al., 1995) and for the cities of Seville and Granada during the period 1601–1650 AD (Rodrigo et al., 1994).

## 4. Discussion

The only absolute proof of the reliability of these results is to show that they agree with the contemporary instrumental data, which are, unfortunately, nonexistent. The best check is therefore to see if other evidence exists that shows similar characteristics the present results. Such other evidence must be derived from different data sources (Fritts et al., 1979; Wang and Zhang, 1992). The climatological information is different if we use different "proxy" data, and therefore the reconstructions will correlate only in a general way (Baron, 1992).

The tree-ring analysis of "Pinus nigra Arnold" in the Sierra de Cazorla mountains (Creus Novau and Puigdefábregas Tomás, 1984) is a proxy for the rainfall from autumn to summer. The Sierra de Cazorla mountains are located in the Guadalquivir River springs and reflect the pluviometric conditions for Western Andalusia (Castillo Requena, 1989). In Fig. 6 the 10 year moving average of the tree-ring width index is shown. The minimum values of the ring-width index correspond to blocked circulation in a zone typical of droughts, and the maximum values correspond to wet conditions. If we compare Fig. 6 with our reconstructions we find a good correspondence between the position of the maxima and minima. We can see that minima in the tree-ring series correspond to the historical droughts in 1540, 1655 and 1680. On the other hand, the two series show maxima around the beginning of the 16th century, 1560, 1590, 1650 and 1670. The general conclusion is increased wetness in Andalusia during the LIA, more marked in Western Andalusia than in Eastern Andalusia.

A comparison with historical data from other zones can be useful for verifying the reconstructions. Analysis of the climate history in the Spanish Plateau (Alvarez Vázquez, 1986), Catalonia (Giralt, 1958; Barriendos, 1994) and Southern France (Le Roy Ladurie, 1983) shows a dry and arid period between 1530 and 1550, cold and wet conditions around 1570, increased wetness at the end of the 16th century and the beginning of the 17th century, and an important drought in the 1680s. According to Lamb (1977), there is evidence in Southern Europe of enhanced variability from year to year and decade to decade, particularly with regards to rainfall. The beginning of the

LIA was characterized by a marked increase in frequency of severe winters and instability during the period 1570–1614 AD in Northern Italy (Camuffo and Enzi, 1992). Records of Tiber floods shows the maximum in winter for the period 1230–1870 AD (Pavese et al., 1992). Analysis of dendroclimatic evidence in Morocco shows some precipitation peaks coinciding with low temperatures in the European area (Serre-Bachet et al., 1992), particularly for the period 1675–1715 AD, when many winters were specified as "wet" or "severe" in Crete, although it is difficult to be sure that they were wetter than the 20th century norm (Grove and Conterio, 1992). The incidence of extremes could differ markedly in the Eastern and Western Mediterranean. The LIA was certainly characterised by a marked variability with increased spatial variations, and a more detailed comparison between different areas in the Mediterranean region is necessary to provide a complete picture of the climate during the LIA.

The reconstruction presented here is not definitive because we do not have an overlapping period between the historical and the instrumental data. When the index series can be extended to the present, an appropriate calibration method will then be used. The longest instrumental series in Andalusia began at the end of the 18th century and the beginning of the 19th century, in Gibraltar in 1791 and San Fernando (Cádiz) in 1805 (Wheeler and Martin-Vide, 1992) and an intense research work focused in this period is still necessary. The study of the contrasts between dry and wet spells and between the two zones in Andalusia allows an analysis of the general characteristics of the interannual and spatial variability in the historical period. On the other hand, given the irregular distribution of rainfall through the year, it is also necessary to develop reconstructions for each season of the year, to study the intra-annual variability of the rainfall regime in Andalusia. This is the aim of further work, now in preparation.

**Acknowledgments**

The instrumental series of annual rainfall in Tablada (Seville) and Armilla (Granada) were provided by the Spanish National Institute of Meteorology. The authors wish to express their gratitude to referees for their useful comments.

**Appendix 1: Data Sources**

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

CODE. Title in English.
Original title (year of publication), author (dates of birth and death) Additional bibliographic references.

UA-1. *Annals of Granada.*
*Anales de Granada*, F. Henríquez de Jorquera (1594–1646).
Marín Ocete, A., ed., 1934: Granada, Universidad de Granada.

UA-2. *Accounts of Seville. Memorias de Sevilla*, some anonymous contemporary authors.
Morales Padrón, F., ed., 1981: Córdoba, Publicaciones del Monte de Piedad y Caja de Ahorros de Córdoba.

UA-3. *Annals of Seville.*
*Anales de Sevilla* (1677), D. Ortiz de Zúñiga (1633–1680).
Espinosa y Cárzel, A. M., ed., 1975: Sevilla, Imprenta Real, 5 vol. (with an appendix of the editor for the period 1677–1700).

CH-1. *History of Cádiz.*
*Historia de la Ciudad de Cádiz* (1598), A. Orozco.
Cádiz, Ayuntamiento de Cádiz, 1845.

CH-2. *Accounts from the City of Utrera.*
*Memorial de la Villa de Utrera* (1604), R. Caro (1573–1647).
Menéndez Pelayo, M., ed., 1883: *Obras de Rodrigo Caro.* Sevilla, Sociedad de Bibliófilos Andaluces.

CH-3. *Antiquity and Excellence of Granada.*
*Antigüedad y Excelencias de Granada* (1608), F. Bermúdez de Pedraza (1585–1655). Property of the University of Granada Library.

CH-4. *History of Jaen.*
*Historia de Jaen* (1628), B. Ximénez Patón (1569–1640).
Ed. facsímil, Ortega y Sagrista, R., ed., 1983: Jean, Riquelme y Vargas.

GH-1. *General History of Spain.*
*Historia General de España* (1623), J. de Mariana (1536–1624). Property of the University of Granada Library.

GH-2. *Continuation of the General History of Spain.*
*Continuación de la Historia General de España* (1733), M. Miñana (1671–1730). Real Bibliotheca, Madrid, 1794. Property of the University of Granada Library.

RH-1. *Sanctuary of Our Lady.*
*Santuario de Nuestra Señora* (1622), R. Caro (1573–1647).
Menéndez Pelayo, M., ed., 1883: *Obras de Rodrigo Caro*, Sevilla, Sociedad de Bibliófilos Andaluces.

RH-2. *Ecclesiastical History of Granada.*
*Historia Eclesiástica de Granada* (1638), F. Bermúdez de Pedraza (1585–1655). Property of the University of Granada Library.

RH-3. *Chronicle of the Franciscan Province of Granada.*
*Crónica de la Provincia Franciscana de Granada* (1683), A. de Torres (1633–1683?). Ed. facsimile, 1984: Granada, Editorial Cisneros.

R-1. *Shipwreck of the Spanish Armada in La Herradura.*

Calero Palacios, M. C., ed., 1974: *Naufragio de la Armada Española en la Herradura (Almuñecar). Aportación Documental.* Granada: Diputación Provincial de Granada, Ayuntamiento de Almuñecar.
R-2. *Texts of the 17th century.*
Simón Díaz, J., ed., 1972: *Impresos del Siglos XVII*, Madrid, CSIC.
R-3. *Historical relations of the 16th and 17th Centuries.*
Uhagón, F. R., ed., 1896: *Relaciones Históricas de los Siglos XVI y XVII*, Madrid: Sociedad de Bibliófilos Españoles.
R-4. *Huracan in Granada.*
*Relación del Admirable Huracán y Espantoso Terremoto de Agua, y Viento que por secretos Juyzios de Dios Nuestro Señor Vino sobre la Ciudad de Granada* (1629), anonymous. Property of the University of Granada Library.
A-1. *Books of Actas of the City Chapter House of Loja.*
Rosal Pauli, R. D., Derqui del Rosal, F., eds., 1989: *Noticias Históricas de Loja (desde sus orígenes hasta el año 1600)*, Granada: Ayuntamiento de Loja, diputación Provincial de Granada.
A-2. *Books of Acts of the City Chapter of Granada.*
Jiménez Vela, R., ed., 1987: *Indices de los Libros de Cabildo del Archivo Municipal de Granada, 1518/1566*, Granada: Universidad de Granada. Sáez Antequera, M. A., ed., 1988: *Indices de los Libros de Cabildo del Archivo Municipal de Granada, 1604/1618*, Granada: Ayuntamiento de Granada.
A-3. *Annals of the Ecclesiastic Chapter House of Malaga.*
Llordén, F., ed., 1988: *Historia de Málaga. Anales del Cabildo Eclesiástico Malagueño*, Granada.
A-4. *Relation of the villages of Spain.*
Viñas, C., Paz, R., eds., 1971: *Relaciones Histórico-Geográfico-Estadí*sticas de los Pueblos de España *Hechas por Iniciativa de Felipe II*, Madrid, Instituto de Sociología "Balmes" e Instituto de Geografia "Juan Sebastiaín Elcano", CSIC.
A-5. *Economical History of Andalusia.*
Ponsot, P., ed., 1986: *Atlas de Historia Económica de la Baja Andalucía*, Granada: Editoriales Andaluzas Unidas.

## Appendix 2: Some Typical Description of Anomalies in the Original Language (Ancient Spanish)

*1) Source UA-1. page 540, index −2*
"la cosecha de trigo en general fue en este año muy corta en el Andalucia y en particular en esta ciudad de Granada por la gran seca y falta de agua, que no se sembraron los secanos, y si se sembraron se perdio la simiente. Cogiose algun trigo en los riegos de la Vega, aunque llego a valer un riego veinte y veinte y cinco ducados y no se alcançaba porque las fuentes no daban agua y los rios se medio secaron. Murio mucho ganado por la falta de las yeruas; empeço a tomar valor el trigo y el pan se subio en Granada y se iba subiendo cada dia ⋯"

*2) Source A-2, index −1*
"a causa de no haber llovido este invierno, los panes tienen necesidad de agua, se acuerda que no se rieguen las heredades hasta regarse los panes"

*3) Source UA-3, Vol. 3, page 387, index +1*
"Entro el otoño con excesivas lluvias en toda España, en Sevilla tan copiosas, que causaron grandisimos daños en edificios y campos".

*4) Source UA-2, pages 51–54, index +2*
"En 25 de Enero fue la venida grande. Auia llovido mucho desde 17 de Enero. Juebes 22 salio el rio, i continuando la lluvia i viento, y creciendo el rio ⋯ Domingo 25 de Enero amanecio anegada la ciudad ⋯".

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