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RAINFALL VARIABILITY IN SOUTHERN SPAIN ON DECADAL TO CENTENNIAL TIME SCALES

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ABSTRACT

In this work a long rainfall series in Andalusia (southern Spain) is analysed. Methods of historical climatology were used to reconstruct a 500-year series from historical sources. Different statistical tools were used to detect and characterize significant changes in this series. Results indicate rainfall fluctuations, without abrupt changes, in the following alternating dry and wet phases: 1501–1589 dry, 1590–1649 wet, 1650–1775 dry, 1776-1937 wet and 1938–1997 dry. Possible causal mechanisms are discussed, emphasizing the important contribution of the North Atlantic Oscillation (NAO) to rainfall variability in the region. Solar activity is discussed in relation to the Maunder Minimum period, and finally the past and present are compared. Results indicate that the magnitude of fluctuations is similar in the past and present. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: regional rainfall anomalies; Little Ice Age; Maunder Minimum; North Atlantic Oscillation (NAO)

1. INTRODUCTION

The third session of the Conference of the Parties to the UN Framework Convention on Climate Change in Kyoto, Japan, established the necessity of gathering climatic data on a century scale. Time scales ranging from a week to centuries are needed to elucidate processes governing climatic phenomena such as droughts or floods, and to identify the causes of long-term shifts in climate (Schneider, 1998). According to the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1996), further work is needed on the 'systematic collection of long-term instrumental and proxy observations of climate system variables for the purposes of model testing, assessment of temporal and regional variability and for detection and attribution studies' to reduce uncertainties in predicting and detecting future climate change. The present work is an effort in this sense.

This work is the continuation of a previous paper (Rodrigo *et al.*, 1999) where a 500-year precipitation record in southern Spain was reconstructed. In the present paper, the objective is to analyse climatic change phenomena on interannual, decadal and centennial timescales, in search of the mechanisms governing droughts and floods. The period from 1500 onwards includes natural climate variations associated with the so-called 'Little Ice Age' (LIA), the Maunder Minimum (when a minimum solar activity was detected), the Industrial Revolution in the 19th century (the beginning of possible anthropogenic influences on climate), as well as the last half of the 20th century, when anthropogenic influence has become evident (Houghton *et al.*, 1996). The analysis of this long series may help to reveal natural causal mechanisms of climatic change, and establish an appropriate comparison between past and present. While most of the palaeoclimatic studies on these time scales focus on temperature (e.g. Mann *et al.*, 1998), the present study adds other climatic variables, such as rainfall. The region analysed is Andalusia (southern Spain), where rainfall is governed primarily by the Azores High and the Atlantic Lows with their associated fronts. Wet/dry periods in Andalusia may be related to cold/warm periods in the Northern Hemisphere. In this sense, the recent positive temperature anomalies over the North Atlantic and

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surrounding land masses and recent dry winter conditions over southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the North Atlantic Oscillation (NAO) index since the early 1970s (Hurrell, 1995). The long-term NAO variability is highly important to study climatic variations in Europe (Kapala *et al.*, 1998).

Section 2 presents the data series and its statistical properties (a more complete analysis may be found in Rodrigo *et al.*, 1999). Section 3 is dedicated to identifying possible climatic change situations, applying various statistical tools and to describing the changes in terms of the known concepts of 'trends', 'abrupt changes' or 'fluctuations'. Section 4 presents the results in relation to possible causal mechanisms, with special attention on the NAO, the Maunder Minimum period, and the comparison between past and present climate—that is, before and after the possible onset of anthropogenic influences on climate. Finally, future research perspectives are outlined.

2. DATA

A previous paper (Rodrigo *et al.*, 1999) has reconstructed rainfall in southern Spain from 1500 to the present, using original documentary sources covering mainly the southwestern Iberian Peninsula and the Guadalquivir River Valley (Figure 1). A numeric index was established to characterize rainfall and its evolution. The main events detected were coded, from severe droughts (I = −2) to severe floods (I = +2)

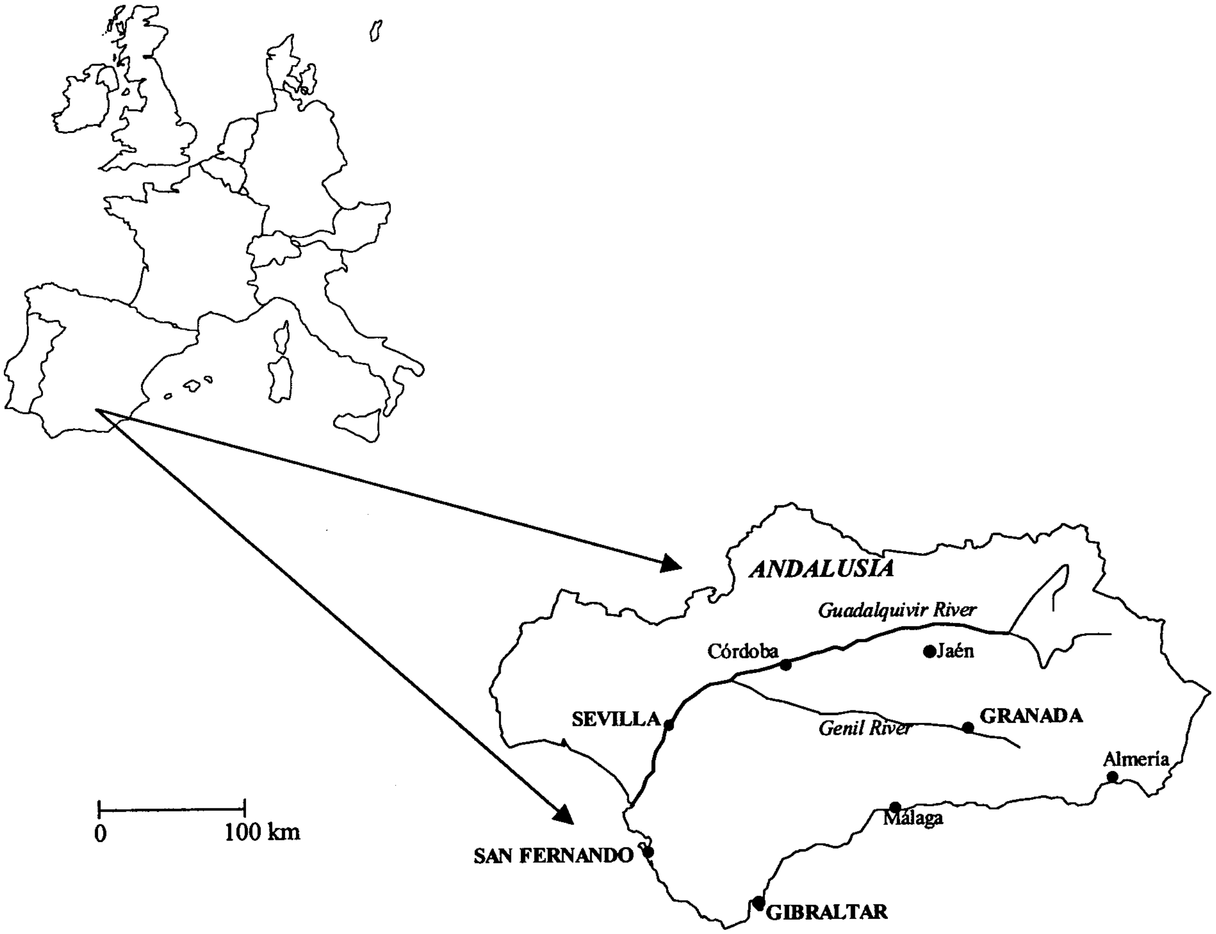

Figure 1. Map of the study region

on a seasonal timescale. An annual index was formulated to summarize the seasonal indices. This indexing covered 1501 to 1850. Instrumental data in the region began in Gibraltar in 1791 and lasted until 1997. By using principal components analysis (PCA), this station was shown to be representative of the region's rainfall variability. Ordinal indices were calibrated with the results of other studies of historical climate and with instrumental precipitation data. The overlapping period 1791–1820 was used to calibrate indices by means of a linear relationship between qualitative indices and instrumental values with the period 1821–1850 being used to validate the calibration. Figure 2 shows the results, expressed as anomalies with regard to the average value of the instrumental period 1951–1980 and the 10-year moving average. This reference period was chosen because it is usually used to normalize the NAO index (Jones *et al.*, 1997). The average value of total annual rainfall in Gibraltar for 1951–1980 is 805.7 mm, the median is 822.5 mm and the standard deviation (S.D.) is 262.7 mm. Although the rainfall series during the reference period cannot be considered to be a sample from a normal population, the results of applying different tests for randomness (runs above and below median, runs up and down, Box–Pierce test) confirm the hypothesis that the reference period series is random at the 90% confidence level.

The 10-year moving average allows a preliminary view of the temporal evolution of rainfall in the region. That is, after several years of prevailing dry anomalies during the 16th century, with a rainfall minimum around 1540, a clear wet period begins at the end of the century, lasting until the mid-17th century. The 18th century is clearly dry, with a minimum around 1750. Afterwards, rainfall anomalies increase, reaching a maximum around 1860. From the late 19th century, rainfall progressively decreased, interrupted only by positive anomalies in the 1960s.

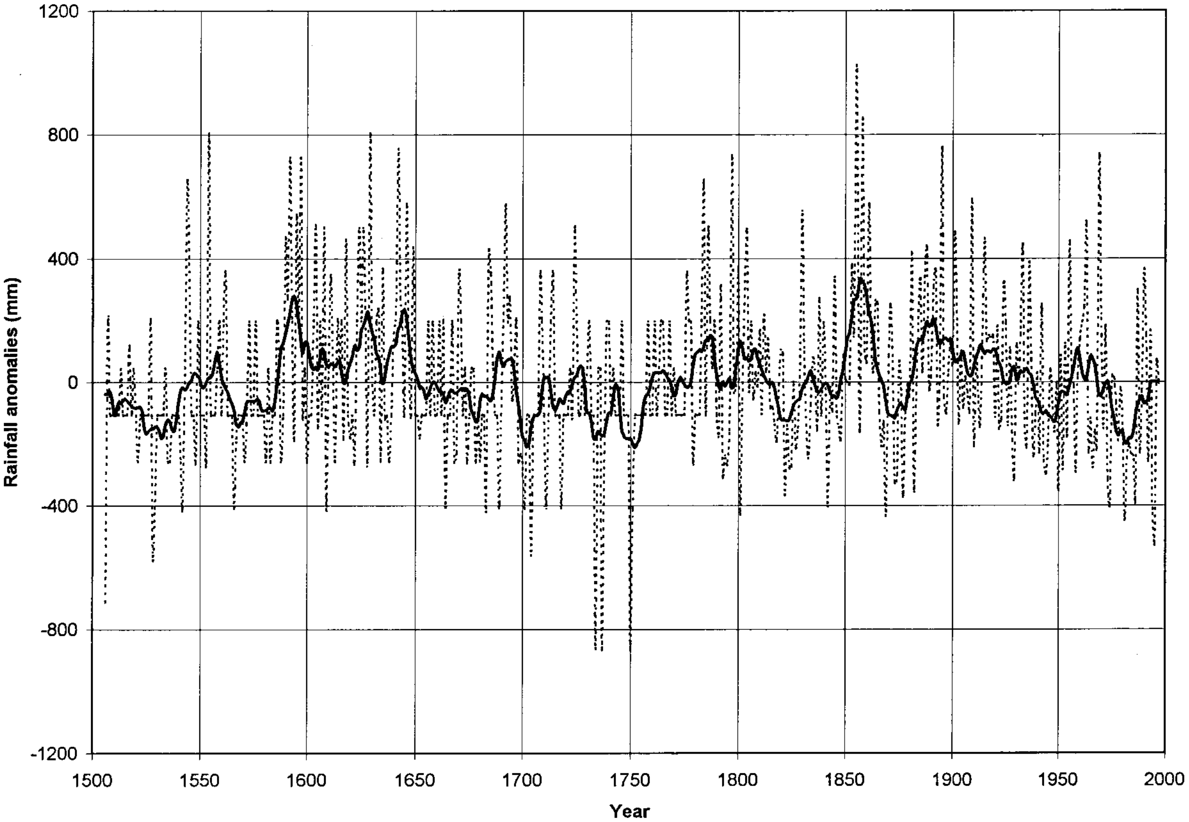

Figure 2. Broken line: rainfall anomalies for the period 1501–1997 with regard to the average value of the instrumental period 1951–1980. Solid line: 10-year moving average

Table I. Statistics of the annual rainfall anomalies for the period 1501–1997 in Andalusia (southern Spain)[a]

Parameter	Value (mm)
Average	−0.3
S.D.	257.9
Minimum	−864.0
Percentile 10%	−257.7
Percentile 25%	−106.1
Percentile 50%	−106.1
Percentile 75%	186.7
Percentile 90%	348.6
Maximum	1025.1
Standard skewness	5.4
Standard kurtosis	6.9

[a] Anomalies are expressed as deviations from the reference period 1951–1980.

Table I shows summary statistics for the series, including measures of the central tendency, variability and shape. The standardized skewness and kurtosis can be used to determine whether the samples come from a normal distribution. Values of these statistics outside the range −2 to +2 indicate significant departures from normality. In this case, the standardized skewness and kurtosis values were not within the range expected for data from a normal distribution. The Chi-Square and the Kolmogorov–Smirnov tests also imply that the series did not come from a normal distribution with 99% confidence. Non-parametric statistics are particularly useful when the data distribution is unknown or not normal (Sneyers, 1992). On the other hand, some tests that were originally developed on the assumption of a normal distribution turned out to be quite robust when applied to data in which the distribution deviated considerably from the Gaussian form. In this sense, the t-test for comparison between means may be considered robust and it may be applied to data having any arbitrary frequency distribution (Mitchell, 1966). In the following sections, non-parametric tools or robust tests are applied to study the temporal evolution of rainfall in the study region.

3. DETECTION AND CHARACTERIZATION OF CHANGES

After climatic reconstruction, the time series was analysed to find behavioural patterns of the variable, and to compare contemporary with historical rainfall. The objective was to identify possible climatic change situations. First, the sum of cumulative deviations was calculated. If two subperiods showed a significant change of their average values, this was reflected in a change of slope in the curve that represents the cumulative deviations against time. The change point was the year having an extreme value (Bárdossy and Caspary, 1990). This method has been useful to analyse rainfall and runoff series in which high variability may mask long-term trends (Mitchell, 1966). However, this method does not identify the character of the change or the stability of the series before and after the change point, and thus the results should be considered with caution (Sneyers, 1992). Figure 3 represents the computed sums of cumulative deviations. The result indicates the most notable changes in the slope of the curve in the years 1589 (absolute minimum of the cumulative deviations), 1649 (maximum in the 17th century), 1775 (minimum in the 18th century) and 1937 (absolute maximum of the cumulative deviations). Table II shows the number of years and basic statistics of each. The length of these periods reveals no regular pattern. Average and median values indicate that the periods 1501–1589, 1650–1775 and 1938–1997 are dry in relation to the reference period, while 1590–1649 and 1776–1937 may be considered wet. The definition of a wet or dry period affects not only the mean values, but also the extreme values. Thus, in general terms, dry periods showed the lowest minimum values, and wet periods the highest maximum values. Skewness and kurtosis coefficients indicate the non-normal character of most of these periods.

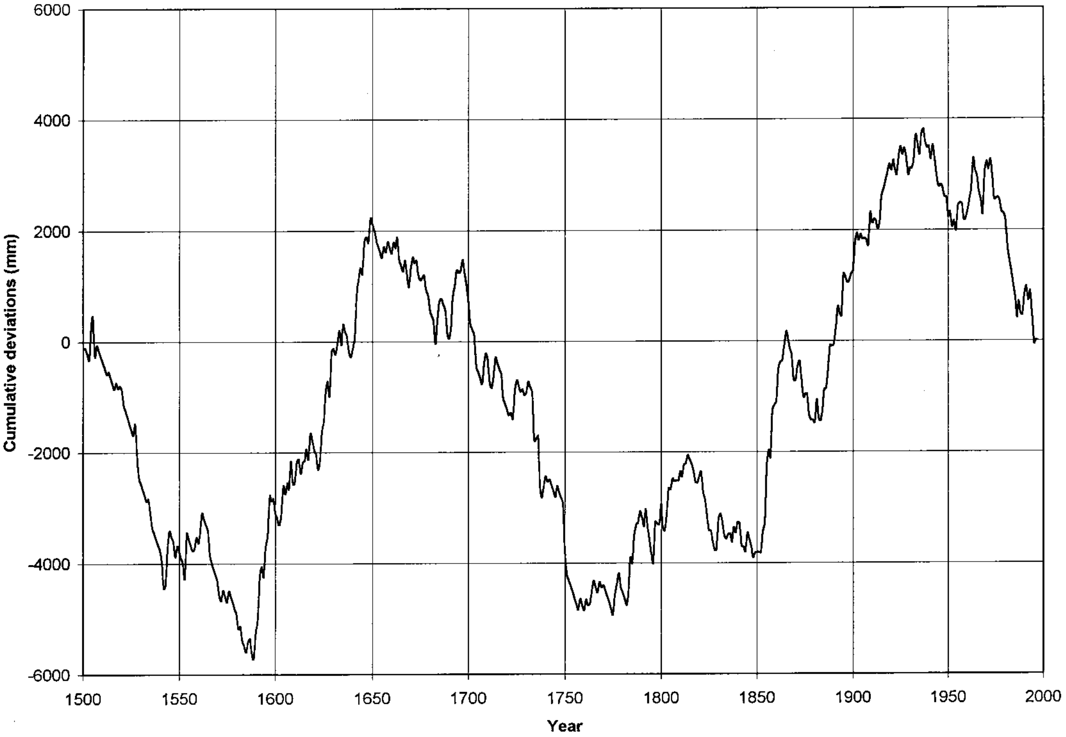

Figure 3. Sum of cumulative deviations for the southern Spain rainfall, 1501–1997

Table II. Periods detected by applying sum of cumulative deviations (values expressed in mm as deviations from the average of the reference period 1951–1980)

	1501–1589	1590–1649	1650–1775	1776–1937	1938–1997
n (years)	89	60	126	162	60
Average	−65	132	−57	54	−64
S.D.	219	299	233	255	249
Median	−106	178	−106	7	−108
Minimum	−712	−409	−864	−436	−524
Maximum	803	803	576	1025	730
Standard skewness	4.2	1.4	−2.6	4.6	2.5
Standard kurtosis	8.1	−0.9	5.9	3.4	1.2

To confirm the existence of these changes, a t-test of difference between the means was applied. This test involves a comparison of two different periods, before and after a possible change point. To confirm unsteadiness, the condition $|t_d| > t$ must be verified, where t_d is the defined statistic to verify the null hypothesis of randomness, and t is Student's t. Table III shows the results of applying this test to pairs of successive subperiods within the overall period studied. Each period proved to be significantly different from the previous one, because in all the cases the alternative hypothesis (statistically significant difference) was verified. In the second period, a negative sign of the difference suggests an increase in rainfall, and a positive sign a decrease. The second period (1590–1649) deserves special mention, because not only the differences between means are statistically significant, but also the S.D.s, as indicated by the F-test (in this case, a t-test was applied without assuming equal variances). These results are similar to findings of other authors. Briffa *et al.* (1990), from tree-ring analyses in Fennoscandia, established a relatively short cold period between 1570 and 1650, with a warmer period before 1570, the main cold

Table III. Comparison between the periods detected, F-test to compare S.D.s and t-test for difference between means (95% confidence levels)[a]

Periods	F-test	Confidence interval for ratio of variances	Difference between means (mm)	t_d	Confidence interval for difference between means
(1501–1589)–(1590–1649)	0.59*	(0.33, 0.85)	−197	−4.36*	(−281, −112)
(1590–1649)–(1650–1775)	1.65*	(1.08, 2.61)	+189	4.32*	(109, 269)
(1650–1775)–(1776–1937)	0.83	(0.60, 1.17)	−111	−3.79*	(−168, −53)
(1776–1937)–(1938–1997)	1.05	(0.67, 1.57)	+118	3.06*	(42, 193)

[a] Null hypothesis: equal means and S.D.s (*denotes a statistically significant difference).

period between 1570 and 1620, and normal conditions from 1660 until 1750. In their analysis on values of accumulated areal ice volume along the Baltic coast of Germany, Koslowski and Glaser (1999) found strong phases of increased winter severity in 1593–1630 and 1763–1860, coinciding with wet phases in Andalusia, and decreased winter severity in 1501–1533, 1711–1762 and from 1861 to the present, in accordance with the dry phases in southern Spain. This coincidence suggests that the LIA was characterized in the southern Iberian Peninsula by increased rainfall, with the main phase approximately between 1590 and 1650.

The t-test established different periods (i.e. a change between periods), but, because of the nature of this test, did not specify the character of these changes. Thus, the next step was to determine the nature of the changes detected. In general, three types of changes can be distinguished: abrupt change, trend and fluctuations. The term ‘trend’ refers not only to a linear change, but also to changes with a maximum or minimum at the extreme points of the series. An abrupt change occurs when a trend is present and a change point divides the series into two distinct subseries. The dividing point is an abrupt-change point. This point is found by applying the sequential version of the Mann–Kendall test (Sneyers, 1992), this non-parametric test being the most appropriate for detecting abrupt changes in climatological series (Esteban-Parra *et al.*, 1995). The application of this test (Figure 4) showed that the changes detected were not abrupt, because the graphs of the sequential onward version of the statistical trend test (solid line) and the sequential backward curve (broken line) did not intersect at the 95% significance level. A decreasing

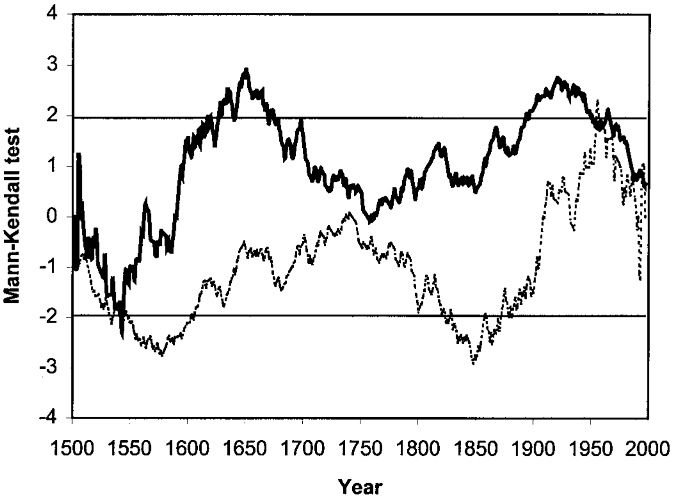

Figure 4. Mann–Kendall test of the rainfall series, period 1501–1997. Solid line: sequential onward version of the statistic trend test; broken line: sequential backward version. The 95% significance level is shown

trend appeared around 1540, an increasing trend that reached its maximum around 1650, and afterwards lost its significance, and again an increasing trend in the first half of the 20th century—that is, a result similar to the dry and wet periods detected with the previous method. These trends were not linear (correlation coefficients and slopes are ~ 0). Over the long term, abrupt changes were not evident. Therefore, the temporal evolution of rainfall may be characterized as fluctuating, with alternating maxima and minima, resulting from non-linear increasing and decreasing trends.

A reliable method of studying time series is via a power spectrum. The standard FFT spectrum was calculated. However, it is an open question whether the results have any physical meaning or are a mathematical artefact, and comparisons of different results may highlight this problem. The spectrum was calculated taking the year as the time unit, so that the results were related to interannual and interdecadal variations. Figure 5 shows the resulting periodogram. Because the lag-one serial correlation coefficient ($r_1 = 0.12$) differed significantly from zero, a null continuum red noise was adopted. Peaks above the 95% confidence level indicated possible significant periodicities—that is, possible mechanisms responsible for the main fluctuations in the series. The greatest part of the total variance accumulated at the lowest frequency, indicating long-term trends, as indicated by the Mann–Kendall test. These long-term trends may be related to the onset of the main phase of the LIA (period 1590–1649) and perhaps with global warming during the 20th century, during which decreasing rainfall (since 1930s) has been detected. In fact, the results of several experiments of high-resolution GCM match the trend during the last years of the 20th century (Houghton *et al.*, 1996). Similar long-term trends masked by other fluctuations have been found by Mächel *et al.* (1998) while analysing the 'centres of action' above the Atlantic area from 1881 to the present.

The other peaks detected in Andalusian rainfall correspond to periodicities of about 16.7, 7–9, 3.5 and 2.1 years. In relation to the interdecadal variability with a period of 16.7 years, Rodríguez-Puebla *et al.* (1998) have found a significant oscillation of 16 years in their analysis of Spanish rainfall for the period 1949–1995 on the Mediterranean coast of the Iberian Peninsula, coinciding with the 16-year period detected in the Southern Oscillation Index (SOI) teleconnection pattern. In fact, an oscillation in the Pacific Ocean with a time scale of 10–20 years and a significant peak of about 18 years were detected in the spectrum of sea-surface temperature (SST) over the North Pacific, from an integration of the Hamburg ECHAM + LSG coupled ocean–atmosphere GCM (von Storch, 1994; Robertson, 1996). Moron *et al.* (1998) found a significant oscillation in North Atlantic SST of about 13–15 years. Therefore, this peak could indicate a mid-latitude air–sea interaction in the Atlantic area. Cycles around 7–9 years and a quasi-biannual oscillation have been found in the analysis of the NAO index (Hurrell and van Loon, 1997; Appenzeller *et al.*, 1998; Cook *et al.*, 1998). Luterbacher *et al.* (1999) reconstructed the monthly NAO index back to AD1675, and found strong decadal to interdecadal variations and

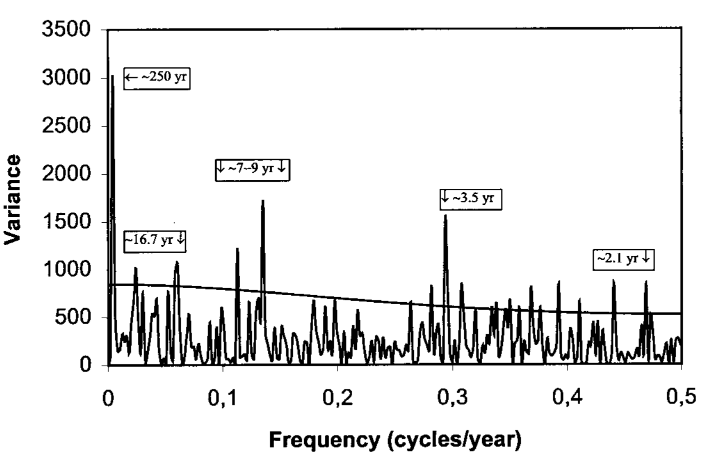

Figure 5. Power spectra of the rainfall anomalies for the period 1501–1997. The 95% significance level is shown

significant spectral power between 54 and 68 years in the annual mean NAO index. According to these authors, further studies are needed to clarify whether their results were affected by shortcomings of their data base and/or reconstruction method. Finally, the SST of the Mediterranean from 1950 to 1988 shows a periodicity of about 3.1 years (Makrogiannis and Sahsamanoglou, 1990), and the main values of pressure of the Azores High show a periodicity of about 4 years (Sahsamanoglou, 1990). Therefore, it is plausible to associate these periodicities with the Atlantic 'centres of action', the NAO and ocean–atmosphere interactions.

4. DISCUSSION

The periodicities found closely agree with the results of spectral analysis applied to the behaviour of Atlantic action centres and the NAO index, this index usually being defined for the winter season (Hurrell, 1995; Jones *et al*., 1997). In a previous paper (Esteban-Parra *et al*., 1998), the correlation coefficients between the NAO index computed by Hurrell (1995) and a series of precipitation in Spain were calculated. The results, significant at 95% confidence level, for the study region gave -0.55 for annual rainfall, and -0.67 for winter rainfall. From a Canonical Correlation Analysis, Zorita *et al.* (1992) found similar correlations and established that the NAO pattern is the most important atmospheric phenomenon in the Atlantic area associated with Iberian winter rainfall. Therefore, the high-index values can be related to low annual and winter precipitation (drought), and the low-index values to intense rainfall and so floods. This inverse relationship appears because westerlies, associated with high-index values, are associated with an intensification of the high pressure system over the western Iberian Peninsula, producing blocking situations over the study area. By contrast, low-index values, and intensified meridional circulation, shift the Atlantic cyclone track southwards, invading the Iberian Peninsula, and causing intense rainfall and so floods. Table IV shows the NAO winter index values corresponding to very dry and very wet winters in Gibraltar from the period 1864–1997. Very dry and wet winters are defined according the percentile distribution of rainfall at this station ($< P_{10}$ and $> P_{90}$, respectively). Extreme NAO index values are defined as those outside the interval $(\bar{x} - \sigma, \bar{x} + \sigma)$ where $\bar{x}$ is the mean value and σ the S.D. of the NAO winter index. The mean value was -0.03 and the S.D. of the NAO index was 1.8. Very wet winters were associated with negative values, except in 1912, 1933 and

Table IV. NAO winter index corresponding to very wet and very dry winters in Gibraltar for the period 1864–1997[a]

Very dry winters			Very wet winters		
Year	Rainfall (mm)	NAO index	Year	Rainfall (mm)	NAO index
1869	141	+1.46	1881	708	−3.87
1875	165	−1.50	1886	661	−1.28
1906	99	+1.80	1895	680	−4.01
1919	170	−0.97	1912	602	+0.06
1925	146	+2.12	1918	762	−0.97
1931	112	−0.34	1933	672	+0.07
1943	140	+1.24	1959	699	−0.55
1957	137	+1.27	1963	931	−3.66
1961	110	+1.56	1964	628	−2.94
1973	159	+2.24	1969	757	−4.90
1981	15	+1.77	1977	639	−2.28
1983	139	+4.13	1990	798	+3.66
1994	146	+2.03			
1995	44	+3.37			

[a] Very wet winters defined as those with rainfall >percentile 90% (=598 mm), and very dry winters defined as those with rainfall <percentile 10% (=180 mm) of the period 1864–1997.

1990; very dry winters were associated with positive values, except in 1875, 1919 and 1931. However, exceptions were associated with low index values, very close to the mean value or within the normal interval ($\bar{x} - \sigma, \bar{x} + \sigma$). Only 1990 presents an apparent contradictory situation. That is, 50% of the very wet winters were associated with an extreme negative NAO values, and 40% of the very dry winters were associated with an extreme positive NAO index. In this sense, a recent reconstruction of the NAO index for the past 350 years from ice cores in Greenland (Appenzeller *et al.*, 1998) has shown the highest values of the NAO index occur around 1695, in the early 18th century and 20th century, and the lowest values around 1680, 1880 and 1960. According to Koslowski and Glaser (1999), the identification of variations in ice winter severity along the German Baltic coast indicate the probable state of the NAO: periods of low ice production (1501–1553, 1711–1762) are strongly correlated with strong westerlies, and heavy ice production (1593–1630, 1763–1880) with weak westerlies. In general terms, these results coincide with the appearance, respectively, of dry and wet periods in the Andalusian data. The NAO is responsible for generating systematic large-scale anomalies in wind speed and latent and sensible heat fluxes, and, therefore, is related to feedback mechanisms between ocean and atmosphere. According to Hurrell (1996) the mechanisms of hemispheric warming amplifies the NAO in the Atlantic sector. Moron *et al.* (1998) found a 7.5 year oscillation in North Atlantic SST, and related this oscillation to the interannual variability of the NAO index, although these authors recognize that the interaction of such an SST oscillation with the atmosphere above deserves further exploration. Other features require more thorough research, as, for example, the statistical comparison with other reconstructions, in particular the recent reconstructions of the NAO index (Appenzeller *et al.*, 1998; Cook *et al.*, 1998; Luterbacher *et al.*, 1999).

In relation to the Maunder Minimum (1645–1715), a period inside the LIA in which the solar activity decreased notably, many studies on climatic change have emphasized solar activity as a cause of climatic change (Eddy, 1976; Reid, 1993). In addition, to support these ideas, spectral analysis of many meteorological variables reveals significant peaks having periodicities similar to those of solar activity (11, 22 years). In the present case, the Maunder Minimum is included in one of the dry periods detected, and does not seem exceptional within the overall series. The evolution of rainfall is highly variable, with severe droughts (1664, 1683, 1689, 1704, 1711) and floods (1646, 1649, 1684, 1692). This high variability has been detected not only in southern Spain, but also in other parts of Europe, such as in Italy (Camuffo and Enzi, 1994). The mean value of rainfall anomalies in Andalusia for this period is -25 mm and the S.D. is 239 mm, values very similar to those of the entire series. When this period is compared with other periods of similar length, such as the immediately preceding period, 1575–1644, the period immediately afterward, 1716–1785, and the last 70 years in the 20th century, the following results were found: the *t*-test of difference between means established a significant difference with respect to the period 1575–1644. This difference is a consequence of the wet character of the period from the last decades of the 16th century to the first half of the 17th century—that is, the interval that has been characterized as the main phase of the LIA in Andalusia. The difference with respect to the period 1716–1875 is not significant, and the result is similar when compared with the instrumental values for the period 1927–1997. In no case is there a statistically significant difference between the two S.D.s; thus, in comparing means, it is assumed that the variances of the two samples are equal. Consequently, the Maunder Minimum period was not exceptional in the context of the overall record, and, therefore, it cannot be affirmed that the decreasing trend of solar activity during the Maunder Minimum had a notable influence on Andalusian rainfall. A similar result was reported after analysing temperature reconstructions from tree rings in western and southern Europe (Serre-Bachet, 1994). According to some authors (Lansberg, 1984; Legrand *et al.*, 1990), the Maunder Minimum did not affect the LIA climate. However, other authors (Appenzeller *et al.*, 1998; Koslowski and Glaser, 1999) have detected a clear Minimum Maunder signal in their analysis from ice cores in Greenland (highest value of the proxy index around 1695) and ice volume along the German Baltic coast (increased winter severity in 1655–1710). This is a major discrepancy with regard to Andalusian data. A possible explanation is that only a few extremely warm and cool decades were synchronous over the entire continent (Jones and Bradley, 1992).

Table V. Comparison between dry and wet periods detected, *F*-test to compare S.D.s and *t*-test for difference between means (95% confidence levels)[a]

Periods	*F*-test	Confidence interval for ratio of variances	Difference between means (mm)	t_d	Confidence interval for difference between means
(1501–1589)–(1938–1997)	0.78	(0.48, 1.23)	−1	−0.02	(−77, 76)
(1650–1775)–(1938–1997)	0.87	(0.55, 1.33)	+7	+0.18	(−67, 80)
(1590–1659)–(1776–1937)	1.38	(0.92, 2.15)	+78	1.94	(−1, 158)

[a] Null hypothesis: equal means and S.D.s (*denotes a statistically significant difference).

Perhaps solar activity is more influential at high latitudes, or on hemispheric or global scales. However, recent analyses from the measurement of total solar irradiance, compiled by five independent space-based radiometers since 1978–1996, indicate that total irradiance forcing is unlikely to be the cause of global warming in the last decade (Fröhlich and Lean, 1998). According to Tol and Vellinga (1998), from a statistical analysis of the influence of the sun on climatic change, the solar hypothesis loses plausibility.

Now it is possible to compare historical and modern periods. Table V shows the *t*-test results of the difference between means applied to compare dry historical periods 1501–1589 and 1650–1775 with the recent dry period 1938–1997, and the wet periods 1590–1649 and 1776–1937. The results show no significant difference between historical and modern periods—that is, fluctuations in the 20th century precipitation in southern Spain are similar to those in the past, at least with regard to the mean value. Whether these variations are caused by natural or anthropogenic forcing remains an open question. In any case, the results appear to indicate that the magnitude of the changes is similar in both the past and the present.

5. CONCLUSIONS

The main conclusions of this work are the following:

(i) Rainfall in Andalusia (southern Spain) shows a fluctuating time evolution, with alternate dry and wet periods. Differences between mean values of these periods (1501–1589 dry, 1590–1649 wet, 1650–1775 dry, 1776–1937 wet and 1938–1997 dry) are statistically significant. With slight differences, these phases coincide with other results found in the literature. Abrupt changes over the long term were not detected.

(ii) The main phase of the LIA corresponds to the period 1590–1649, characterized by wet conditions, with higher flooding frequency.

(iii) Spectral analysis shows that the main periodicities in the data series correspond to fluctuations of about ~16.7, 7–9, 3.5 and 2.1 years. These fluctuations are superimposed to non-linear long-term trends.

(iv) Among the possible causal mechanisms of rainfall fluctuations in the region, the NAO behaviour is the most remarkable, and in particular extreme values of the NAO index are related to droughts (positive extreme NAO) and floods (negative extreme NAO).

(v) The Maunder Minimum (1645–1715) does not appear to be exceptional in the context of the entire series, indicating that solar activity is unlikely to be the cause of climatic changes in the study region.

(vi) 20th century rainfall anomalies show a behaviour similar to that of other periods in the past.

The close relationship between extreme NAO values and precipitation anomalies over southern Spain could be used to reconstruct a longer record of the NAO index, than is now available, or, at least, to validate the existing reconstructions. This is an objective of future work. The possibility of monitoring the long-term NAO variability over an extended period when human influence is negligible may have implications for comparisons between the past and the present, and, therefore, for climate predictions.

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REFERENCES

Appenzeller C, Stocker TF, Anklin M. 1998. North Atlantic Oscillation dynamics recorded in Greenland ice cores. *Science* **282**: 446–449.

Bárdossy A, Caspary HJ. 1990. Detection of climate change in Europe by analysing European atmospheric circulation patterns from 1881 to 1989. *Theoretical and Applied Climatology* **42**: 155–167.

Briffa KR, Bartholin TS, Eckstein D, Jones PD, Karlen W, Schweingruber FH, Zetterberg P. 1990. A 1400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* **346**: 434–439.

Camuffo D, Enzi S. 1994. The climate of Italy from 1675 to 1715. In *Climatic Trends and Anomalies in Europe 1675–1715*, Frenzel B, Pfister C, Glaser B (eds). Gustav Fischer Verlag: Stuttgart.

Cook ER, D'Arrigo RD, Briffa KR. 1998. A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* **8**: 9–17.

Eddy JA. 1976. The Maunder Minimum. *Science* **192**: 1189–1202.

Esteban-Parra MJ, Rodrigo FS, Castro-Díez T. 1995. Temperature trends and change points in the Northern Spanish Plateau during the last 100 years. *International Journal of Climatology* **15**: 1031–1042.

Esteban-Parra MJ, Rodrigo FS, Castro-Díez Y. 1998. Spatial and temporal patterns of precipitation in Spain for the period 1880–1992. *International Journal of Climatology* **18**: 1557–1574.

Fröhlich C, Lean J. 1998. The Sun's total irradiance: cycles, trends and related climate change uncertainties since 1976. *Geophysical Research Letters* **25**: 4377–4380.

Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds). 1996. *Climate Change 1995. The Science of Climate Change*. Cambridge University Press, IPCC: Cambridge.

Hurrell JW. 1995. Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science* **269**: 676–679.

Hurrell JW. 1996. Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters* **23**: 665–668.

Hurrell JW, van Loon H. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climate Change Proceedings International Workshop on Climatic Change at High Elevation Sites*, Wengen, Switzerland.

Jones PD, Bradley RS. 1992. Climatic variations over the last 500 years. In *Climate since A.D. 1500*, Bradley RS, Jones PD (eds). Routledge: London and New York; 649–665.

Jones PD, Jónsson T, Wheeler D. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology* **17**: 1433–1450.

Kapala A, Mächel H, Flohn H. 1998. Behaviour of the centres of action above the Atlantic since 1881. Part II: associations with regional climate anomalies. *International Journal of Climatology* **18**: 23–36.

Koslowski G, Glaser R. 1999. Variations in reconstructed ice winter severity in the Western Baltic from 1501 to 1995, and their implications for the North Atlantic Oscillation. *Climatic Change* **41**: 175–191.

Lansberg HE. 1984. Comments on Wolf's notes for the Maunder Minimum of sunspots and retraction of some earlier claims. Technical Note BN-1019, Institute for Physical Science and Technology, University of Maryland.

Legrand JP, LeGoff M, Mazudier C. 1990. Is there a relationship between the Maunder Minimum and the climatic change observed during the XVIIth century? In *Advances in Geosciences*, Schröeder W (ed.). IAGA: Washington.

Luterbacher J, Schmutz C, Gyalistras D, Xoplaki E, Wanner H. 1999. Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophysical Research Letters* **26**: 2745–2748.

Mächel H, Kapala A, Flohn H. 1998. Behaviour of the centres of action above the Atlantic since 1881. Part I: Characteristics of seasonal and interannual variability. *International Journal of Climatology* **18**: 1–22.

Makrogiannis TJ, Sahsamanoglou CS. 1990. Time variation of the mean level pressure over the major Mediterranean area. *Theoretical and Applied Climatology* **41**: 149–156.

Mann M, Bradley RS, Hughes MK. 1998. Global scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–788.

Mitchell JM. 1966. Climatic Change. WMO Technical Note 79, Geneva.

Moron V, Vautard R, Ghil M. 1998. Trends, interdecadal and interannual oscillations in global sea-surface temperatures. *Climate Dynamics* **14**: 545–569.

Reid GC. 1993. Do solar variations change climate? *EOS* **74**: 23–24.

Robertson AW. 1996. Interdecadal variability over the North Pacific in a multi-century climate simulation. *Climate Dynamics* **12**: 227–241.

Rodrigo FS, Esteban-Parra MJ, Pozo-Vázquez D, Castro-Díez Y. 1999. A 500-year precipitation record in Southern Spain. *International Journal of Climatology* **19**: 1233–1253.

Rodríguez-Puebla C, Encinas AH, Nieto S, Garmendia J. 1998. Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. *International Journal of Climatology* **18**: 299–316.

Sahsamanoglou HS. 1990. Contribution to the study of action centres in the North Atlantic. *International Journal of Climatology* **10**: 247–261.

Schneider SH. 1998. Kyoto protocol: the unfinished agenda. *Climatic Change* **39**: 1–21.

Serre-Bachet F. 1994. Annual and summer mean temperature reconstructions from tree-rings in western and southern Europe since A.D. 1500 with special reference to the late Maunder Minimum. In *Climatic Trends and Anomalies in Europe 1675–1715*, Frenzel B, Pfister C, Glaser B (eds). Gustav Fischer Verlag: Stuttgart.

Sneyers R. 1992. On the use of statistical analysis for the objective determination of climatic change. *Meteorol Zeitschrift* **1**: 247–256.

Tol RSJ, Vellinga P. 1998. Climate change, the enhanced greenhouse effect and the influence of the Sun: a statistical analysis. *Theoretical and Applied Climatology* **61**: 1–7.

von Storch JS. 1994. Interdecadal variability in a global coupled model. *Tellus* **46A**: 419–432.

Zorita E, Kharin V, von Storch H. 1992. The atmospheric circulation and sea surface temperature in the North Atlantic Area in winter: their interaction and relevance for Iberian precipitation. *Journal of Climate* **5**: 1097–1108.