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Reconstruction of rainfall in Zafra (southwest Spain) from 1750 to 1840 from documentary sources

M. I. Fernández-Fernández¹, M. C. Gallego¹, F. Domínguez-Castro¹,
J. M. Vaquero¹, J. M. Moreno González², and J. Castillo Durán²

¹Departamento de Física, Universidad de Extremadura, Spain

²Centro de Estudios del Estado de Feria, Zafra, Spain

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Correspondence to: J. M. Vaquero (jvaquero@unex.es)

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Abstract

This work presents the first high-resolution reconstruction of rainfall in southwestern Spain during the period 1750–1840. The weather descriptions used are weekly reports describing the most relevant events that occurred in the Duchy of Feria. An index was defined to characterise the weekly rainfall. Monthly indices were obtained by summing the corresponding weekly indices, obtaining cumulative monthly rainfall indices. The reconstruction method consisted of establishing a linear correlation between the monthly rainfall index and monthly instrumental data (1960–1990). The correlation coefficients were greater than 0.80 for all months. The rainfall reconstruction showed major variability similar to natural variability. The reconstructed rainfall series in Zafrá was compared with the rainfall series of Cadiz, Gibraltar and Lisbon for the period 1750–1840, with all four series found to have a similar pattern. The influence of the North Atlantic Oscillation (NAO) on the winter rainfall reconstruction was found to behave similarly to that of modern times. Other studies described are of the SLP values over the entire North Atlantic in the months with extreme values of rainfall, and unusual meteorological events (hail, frost, storms and snowfall) in the reports of the Duchy of Feria.

1 Introduction

Knowledge of the climate of past centuries is crucial for a proper understanding of our current climate and its changes due to anthropogenic influences (IPCC, 2007). However, little is known about the climate prior to the mid-nineteenth century when the first meteorological networks were set up in a number of countries and regions. Studies of past climates contribute significantly to the evaluation of climatic processes before the onset of systematic global human influences. Brázdil et al. (2005) categorise the data used in historical climatology as direct or indirect. Direct data may be descriptive documentary data or early instrumental measurements, while indirect data is that

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which reflects the impact of weather on elements of the natural system including the hydrosphere, the cryosphere and the biosphere (Brázdil et al., 2005).

In recent decades, there have been many papers published on historical climatology in Europe (Bradley and Jones, 1992; Pfister and Brázdil, 1999; Brázdil et al., 2005, 2010). A method to reconstruct long rainfall series using systematic descriptive observations in weather diaries was developed by Gimmi et al. (2006). This method was used to reconstruct the precipitation in Bern (Switzerland) for the period 17600–2003. For the Mediterranean area, the paper by Diodato (2007) analyses rainfall during the pre-instrumental period 1675–1868 in southern Italy. Alcoforado et al. (2000) reconstructed the temperature and rainfall in southern Portugal during the Late Maunder Minimum (1675–1715). In Spain, the pioneer in historical climatology research was Manuel Rico Sinobas (1821–1898) who collected climatic information from different historical archives and created a record of climate patterns in the past. Historical climatology in Spain has undergone major growth during the last 20 yr. There have been several attempts to reconstruct rainfall series for various places in Iberia at annual and seasonal scales. These exercises have been based on documentary records because the focus of the few dendroclimate studies in Iberia has been on temperatures (Büntgen et al., 2008). Other natural proxies have been considered. Romero-Viana et al. (2011) reconstructed winter rainfall since 1579 AD based on a laminated calcite sediment from Lake La Cruz (in eastern-central Iberia). A reconstruction of annual rainfall since 1500 AD for Andalusia (southern Iberia) was performed by Rodrigo et al. (1999) using documentary data. Later, Rodrigo and Barriendos (2008) studied the seasonal and annual rainfall variability over the Iberian Peninsula (IP) during the 16th–20th centuries from extreme events reported in documentary sources. However, there has as yet been no reconstructed monthly rainfall series.

The coverage of Iberia in these studies has been irregular, despite the Peninsula's great climatic variability. Most works devoted to considering different regions of Iberia have been biased towards Andalusia (southern Iberia) (Rodrigo et al., 1995; Rodrigo, 2008) or Catalonia (Martín-Vide and Barriendos, 1995, 1998), and the historical climate

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in western Spain (especially the region of Extremadura) has received little attention until now.

In this paper, we present the first high-resolution reconstruction of rainfall series in the IP during the period 1750–1840 using documents related to the administration of the Duchy of Feria, a territory around the town of Zafra (SW Spain). These documents are conserved in the Zafra Municipal Archive.

2 Data

The territory that corresponded to the Duchy of Feria is located in the southwest of the IP. In the 18th century, it consisted of sixteen municipalities located in two separate, but close, geographical areas (Fig. 1). The main region corresponded to 14 of these municipalities including the capital of the Duchy, the town of Zafra and the other smaller region to just two municipalities. In 1567, the fifth Count of Feria was raised to the rank of duke and grandee due to his contributions to the state under Spain's King Felipe II. One consequence was a major modernization of the town of Zafra, including the transformation of the old castle into a Renaissance style palace. Later, in the 17th century, the Dukedom of Feria was united with the Marqueeship of Priego, and finally, in the 18th century, also with the Dukedom of Medinacelli. While Zafra was an industrial and commercial town, the surrounding areas were mainly dedicated to agriculture, in particular, cereal production.

The climate of Zafra is classified as Koppen type Csa (temperate with dry or hot summer) according to the Iberian Climate Atlas (AEMET-IM, 2011). The months which present the highest rainfall values in Zafra are December and January. The average winter monthly rainfall is approximately 80 mm, and the summer monthly rainfall approximately 15 mm (Fig. 1). The North Atlantic Oscillation plays an important role in the winter rainfall of Zafra (Zorita et al., 1992; Trigo et al., 2002; Gallego et al., 2005).

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2.1 Documentary proxy data

The weather descriptions used in this work are weekly reports submitted to the Duke describing the most relevant events occurring in his lands. Sometimes, these reports are more frequent due to problems or urgent tasks. They span the period from 1750 to 1840. They are conserved in a specific section denominated “Consultas y Decretos del Ducado de Feria” of Zafra’s Municipal Archive.

In the early eighteen century, the Duke of Medinacelli had inherited the rights of the House of the Duchy of Feria. Living in Madrid, the capital of Spain, the Duke established an administrative framework in the Duchy for the management of his property. Beginning in 1750, an accountant informed him every week about events in the Duchy of Feria. News about the weather was especially relevant for the Duke because it affected how he had to manage the purchase and sale of cereal grains and other products from Madrid. In particular, knowledge of the weather conditions was essential to estimating the quality of the crops and to the correct management of the trade of cereals and other agricultural products. The accountant lived in Zafra, so that the meteorological information appearing in the documents mainly refers to this town. Only on special occasions, generally when extreme events have occurred, does one find weather information for other locations. Thus, weather information about Zafra appears in 84 of the years between 1750 and 1840. Figure 2 shows the number of available weekly reports per year containing weather information. There are two important gaps in the series: the decade of the 1760s and the early 1770s, and the period 1810–1814 (Fig. 2). These gaps are due to changes in the accountants, who limited themselves to informing the Duke about economic matters in the Duchy of Feria and about the Napoleonic Wars in Iberia, respectively. In summary, there are weather reports for more than 80 % of the weeks of the year for 63 of the 84 yr with reports available (grey bars), for less than 80 % but more than 10 % of the weeks of the year for 14 yr (red bars), and for less than 10 % of the weeks of the year for 7 yr (blue bars). This source, thus, provides reasonably continuous weather information covering nearly a century.

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2.2 Instrumental data

We used instrumental rainfall data from the station located in Zafrá to reconstruct the rainfall during the period 1750–1840. These data were obtained from Spain’s Meteorology Agency (AEMET). The geographical coordinates of the station are 38°25’40” N, 6°24’27” W, 530 m a.s.l. The station has instrumental rainfall data from 1911, but with gaps from 1913 to 1926 and from 1990 to 1997. The RHtestV2 software package (Wang, 2003) was used to test the homogeneity of the rainfall data for the period 1926–2007. This test is based on the penalized maximal t (Wang et al., 2007) and the penalized maximal F (Wang, 2008a) tests embedded in a recursive testing algorithm (Wang, 2008b). The results showed there to exist a changepoint in this data series in 1958. Therefore, the period 1960–1990 was chosen for the reconstruction due to the homogeneity of its data.

3 Data analysis

3.1 The Feria Rainfall Index

The first step in the reconstruction process was to establish a weekly rainfall index from the reports. To this end, we defined three different categories with the following criteria: (a) an index value 0 was assigned to a week with no rainfall; (b) an index value 1 was assigned to a week when the report indicated rainfall on at least one day; and (c) an index value 2 was assigned when a report indicated continual rainfall for the week or heavy rain on at least two days.

Monthly cumulative rainfall indices were obtained by summing the corresponding weekly indices. Since most months had four full reports and a report that corresponded to two months, in these cases the value of the index was estimated proportional to the days belonging to each month. There were 43 months with weather information for only one week of the month. These months were removed from the data series for the purposes of the reconstruction.

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Figure 3 shows the monthly time series of the reconstructed index with the values for each month. In general, the series shows high inter-annual variability. As expected, the months of the winter half of the year (in particular, the six months from November to April, inclusive) present high values of the index, and the summer months low values, especially the two central summer months of July and August (with values close to zero). No clear trends appear in the monthly indices, although one notes that the values of the indices are higher in the central portion of the record (1770–1810) than in the last portion.

Figure 4 shows histograms of the distribution of the frequencies of the monthly rainfall index. The highest index value (8) is only found in January, March, April, November, and December. A high frequency of index 0 is observed in the summer months. It is interesting to note that in April the index 0 appears in only two cases throughout the period of study. This indicates that there was rainfall in almost all the months of April.

3.2 Rainfall reconstruction

Our methodological approach to reconstruction was to establish a linear correlation between the monthly rainfall index and monthly instrumental data. First, we calculated the percentiles from 1 to 99 of the index series for each month, and the same using the instrumental data for each month corresponding to the period 1960–1990 at the Zafrá meteorological station. We then performed a linear correlation study between these two sets of percentiles, setting a significance level of 5 %. The resulting correlation coefficients were greater than 0.80 for all months, with the highest values corresponding to January (0.9782), February (0.9711), November (0.9818), and December (0.9695) and the lowest to the summer months, June (0.8374), July (0.8847), August (0.8344), and September (0.8744). The best linear fit for each month was used to estimate the monthly rainfall (expressed in millimetres).

4 Results

The values of our rainfall reconstruction from 1750 to 1840 in Zafra are shown in Fig. 5. The average rainfall in each season is plotted in Fig. 5a, b, c and d, and the monthly rainfall series in Fig. 5e where the red line represents a 12-month moving average. The great variability observed in this reconstructed rainfall series is similar to the natural variability of rainfall in this region. We identified two wet periods (from 1782 to 1789 and from 1799 to 1807) and two dry periods (from 1796 to 1798 and from 1816 to 1819).

In the first of these wet periods, 1782–1789, the main contributions to rainfall appeared in winter, autumn and spring. Specifically, the seasons that reached the highest values were the winters of 1784 and 1785 (Fig. 5a). The seasonal average rainfall in these years was 172.2 mm and 194.8 mm, respectively. The years that presented the highest values in autumn (Fig. 5b) were 1783 (118.7 mm) and 1786 (120.5 mm), and in spring (Fig. 5c) were 1784 (136.2 mm) and 1785 (122.3 mm).

During the second of the wet periods, from 1801 to 1807, the main contributions to the rainfall appeared in winter and autumn. Specifically, the years that presented the highest values in winter were 1800 and 1804, with average rainfall of 164.6 mm and 154.6 mm, respectively. In autumn, the years that reached the highest values of average rainfall were 1799 (122.4 mm), 1802 (113.0 mm), and 1803 (126.0 mm).

In the dry period 1796–1798, there were low values of rainfall in winter, autumn, and spring. In particular, the lowest of these values corresponded to the winter of 1798, the autumn of 1797, and the springs of 1796 and 1797. In the other dry period, 1816–1819, there were low values of rainfall in all seasons.

By way of comparison of these results with other reconstructions in the literature for this geographical area, the results of Rodrigo et al. (1999, 2000) for Andalusia (southern Spain) showed low rainfall from 1815 to 1850. In their reconstruction of rainfall in Morocco (northwest Africa), Till and Guiot (1990) observe two dry periods, 1779–1798 and 1805–1835, consistent with the low rainfall observed in Zafra in the periods 1796–1798 and 1816–1819.

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4.1 Comparison with rainfall in Gibraltar, Cadiz, and Lisbon

In order to check the reliability of our reconstruction, we compared the rainfall in Zafra, Lisbon, Cadiz and Gibraltar in the current period and during the period 1750–1840 (Fig. 6). All series are located in the southwest of Iberia (see Fig. 1) and have similar patterns of rainfall (Serrano et al., 1999) mainly influenced by the NAO (Zorita et al., 1992; Trigo et al., 2002; Gallego et al., 2005). Figure 6a shows the annual rainfall at these stations in the reference period (1960–1990). As expected, the pattern is similar in all four.

For the period 1750–1840, Cadiz has instrumental monthly rainfall data available from 1805 (Barriendos et al., 2002), Gibraltar from 1813 (Wheeler, 2007) and Lisbon from 1816 (Trigo, 2009), but with a gap from 1826 to 1835. The total annual rainfall in Zafra, Cadiz, Gibraltar and Lisbon in the period common to all the series (1817–1826) can be seen in Fig. 6b. As in the modern period, all four series have a similar pattern. Although a detailed analysis revealed minor differences between the modern and historical periods, in general the quality and reliability of our reconstruction is confirmed by this reproduction of the rainfall pattern for the southwest of the IP.

4.2 Relationship between the rainfall and NAO indices

The NAO plays an important role in determining winter rainfall over the IP. We studied the potential relationship of our reconstruction with the NAO index using two NAO reconstructions (Luterbacher et al., 2002a; Cook et al., 2002) and the classical NAO instrumental index (Jones et al., 1997). The results for the relationship between the average winter rainfall in Zafra and the NAO index are shown in Fig. 7. The solid symbols (discs and diamonds) indicate the relationships corresponding to the instrumental values compiled by Jones et al. (1997) for the modern period (1960–1990; red discs) and for the historical period (1821–1840; blue diamonds). The open symbols (squares and triangles) correspond to the relationships between our rainfall reconstruction and

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the NAO index reconstructions of Luterbacher et al. (2002a) (green triangles) and Cook et al. (2002) (black squares).

In general, the reconstructed indices present a weaker signal for these winter rainfall values than the instrumental index. Also, the reconstructed NAO indices are fairly insensitive to extreme rainfall values. In particular, the extreme values of rainfall in Zafrá for the period 1750–1840 are well connected with the instrumental NAO index, but not with the reconstructed NAO indices. Our rainfall reconstruction could, therefore, help improve the NAO reconstruction for this period.

4.3 Anomalies of Sea Level Pressure over the eastern North Atlantic and Europe for the period 1750–1840

In the previous section, it was noted that the reconstructed NAO indices do not reproduce the extreme rainfall values for the period 1750–1840 very well. We, therefore, performed a study of the Sea Level Pressure (SLP) fields associated with our reconstructed extreme values.

To this end, we used the SLP database developed by Luterbacher et al. (2002b). SLP anomalies relative to the average SLP value in the period 1750–1840 were calculated for the winter months (December, January, February) which had rainfall values above the 95th percentile (Fig. 8, left column) or below the 5th percentile (Fig. 8, right column).

One observes that negative SLP anomalies around southwestern Europe with an anticyclonic circulation over the eastern Atlantic at high latitudes correspond to the winter months with rainfall values above the 95th percentile (left column, Fig. 8). Indeed, this synoptic situation is described by Zorita et al. (1992) as being associated with greater rainfall over the IP. The maps of the winter months with rainfall below the 5th percentile (right column in Fig. 8), show positive SLP anomalies around southwestern Europe. The low-pressure system is displaced to high latitudes, leaving the Iberian Peninsula out of its range of influence, so that the lower reconstructed rainfall values in Zafrá are associated with this synoptic situation.

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4.4 Other weather phenomena

In addition to the exhaustive records of rainfall that we have studied above, the reports of the Duchy of Feria included descriptions of such meteorological events as hail, frost, storms and snowfall. These events may have a major influence on crops, although this will largely be determined by the time of year when they occur. A storm in May, for example, could seriously affect the grain harvest, while the same storm in August would be innocuous. Figure 9 shows, for the period 1750–1840, the number of weeks in each year in which (a) it snowed, (b) it hailed, (c) there were storms, and (d) it froze. We have also included the period 1926–2007 using the information from the Zafra meteorological station taken from AEMET. Note that the weekly weather reports sometimes do not indicate the actual number of days on which these different events occurred, so that it was impossible to construct daily series.

Snow is an infrequent weather event in the climate of Zafra. There were reports of snow for 28 of the 84 yr in the documents. The years of most weeks with snow reports were 1774 and 1832 (3 weeks per year). In the period 1800–1840, the accountants recorded 15 yr with snowfall. Particularly remarkable was a snowfall recorded on 4 February of 1827 in both Cadiz and Zafra (Gallego, 2007). The years in which the accountant recorded most weeks with hail were 1804, 1831, 1836 and 1837 (two weeks per year). In the 84 years with weather descriptions, there were 38 yr with storm reports, mainly recorded in the summer months, and 64 yr with frost reports.

One observes in Fig. 9 that the modern series has a data gap. This corresponded to dates from May 1990 to May 1997. In general, the series do not appear to be homogeneous, even in the modern period (observe, for example, the great variability in the modern frost series). Comparing the historical and the modern period, one sees that the variability and average number of weeks for each weather event type differ considerably between the two periods, especially in the hail and storm series where the historical documents report far fewer weeks than the modern data. Nonetheless, the reason obviously may be that many hail or storm events went unreported by the Duchy's accountant because they had little or no impact on the crops (e.g. some summer storms).

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5 Conclusions

No previous historical climatology study of the Iberian Peninsula has considered the characteristics of the historical climate of southwestern Spain in any detail. Here, we here described a reconstruction of rainfall in southwestern Spain during the period 1750–1840 from a homogeneous source of weather descriptions in the town of Zafra, achieving a particularly fine resolution. The reconstructed rainfall data are available at: <http://salva-sinobas.uvigo.es>. The results revealed two wet periods (from 1782 to 1789 and from 1799 to 1807), and two dry periods (from 1796 to 1798 and from 1816 to 1819). Comparison of the reconstructed rainfall series with the existing instrumental series in southwest Iberia confirmed the reliability and quality of the reconstructed series.

Winter rainfall in Zafra is largely influenced by the atmospheric circulation in the North-Atlantic region. We showed that published reconstructed NAO indices are not entirely consistent with the extreme values of rainfall in southwest Iberia for the period 1750–1840. Therefore, given the location and the quality of our series, it could help to improve the reconstruction of the NAO index for this period. From a wider perspective, we then studied the SLP anomalies over the North Atlantic region corresponding to the months with extreme values of rainfall (below the 5th and above the 95th percentiles) in our reconstruction. The results showed typical synoptic situations that cause extreme rainfall in the southwestern Iberian Peninsula. Our rainfall reconstruction is, therefore, sufficiently precise to be compatible with the published reconstructed SLP fields (Luterbacher et al., 2002b) even in the more extreme cases.

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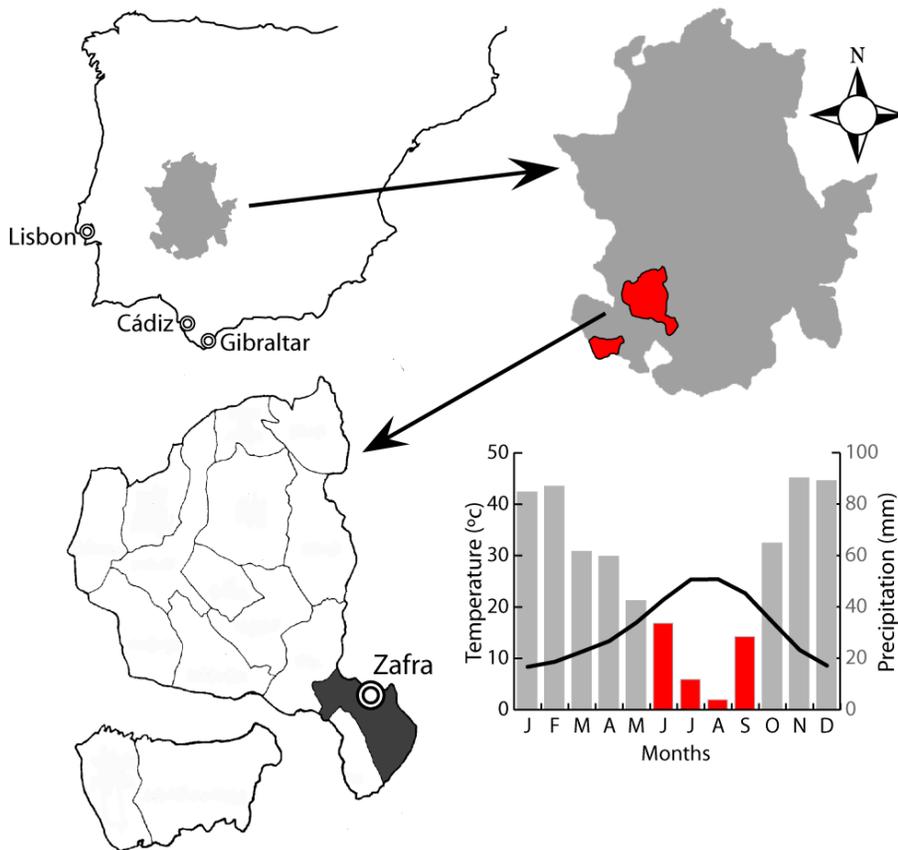


Fig. 1. Duchy of Feria in the second half of the 18th century, and a modern climogram of Zafra.

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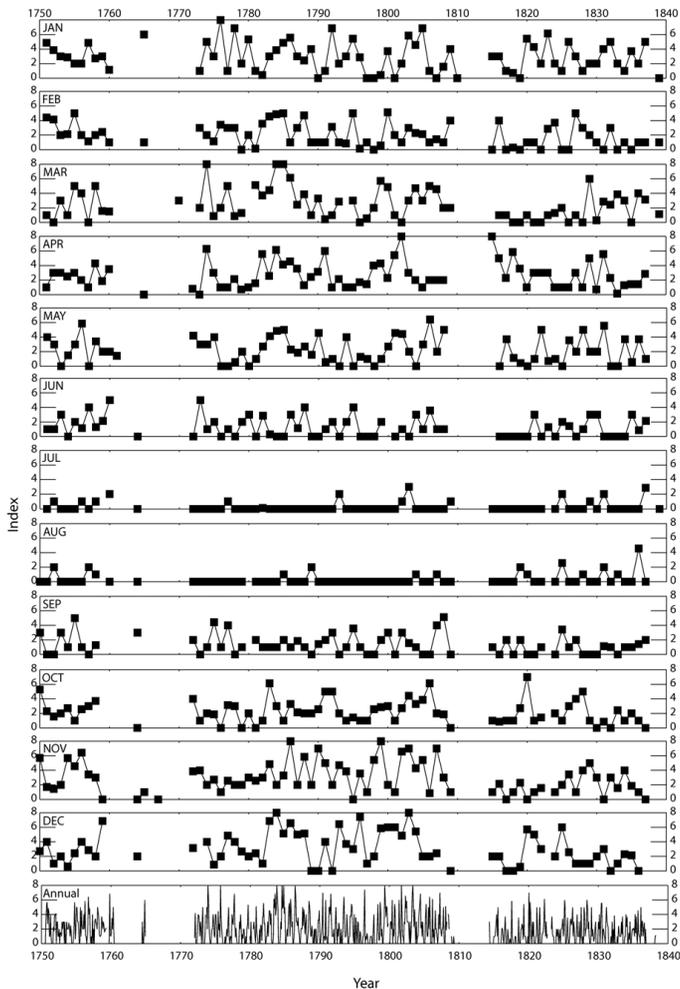


Fig. 3. Monthly time series of the index during the period studied.

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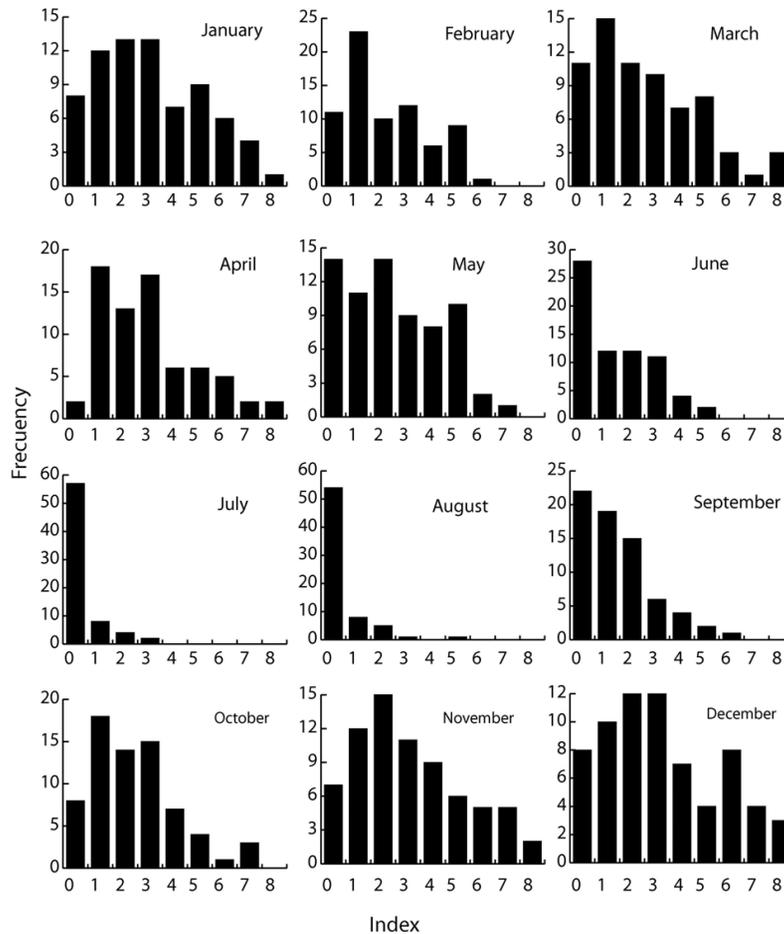


Fig. 4. Histograms of the distribution of frequencies of monthly rainfall indices during the period 1750–1840.

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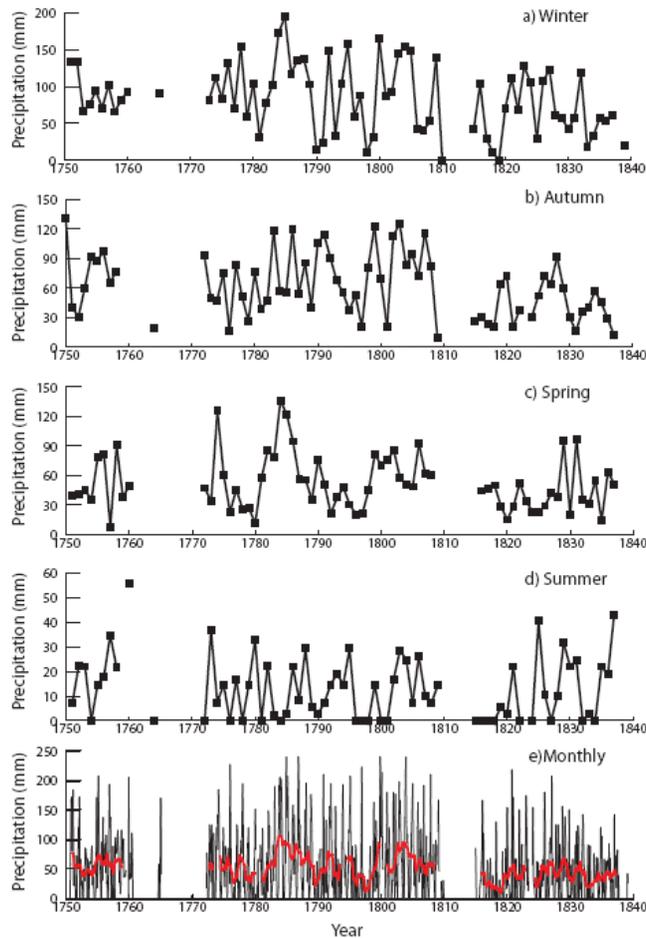


Fig. 5. Estimated rainfall in Zafrá for the period 1750–1840. The red line is the 12-month moving average of the monthly series.

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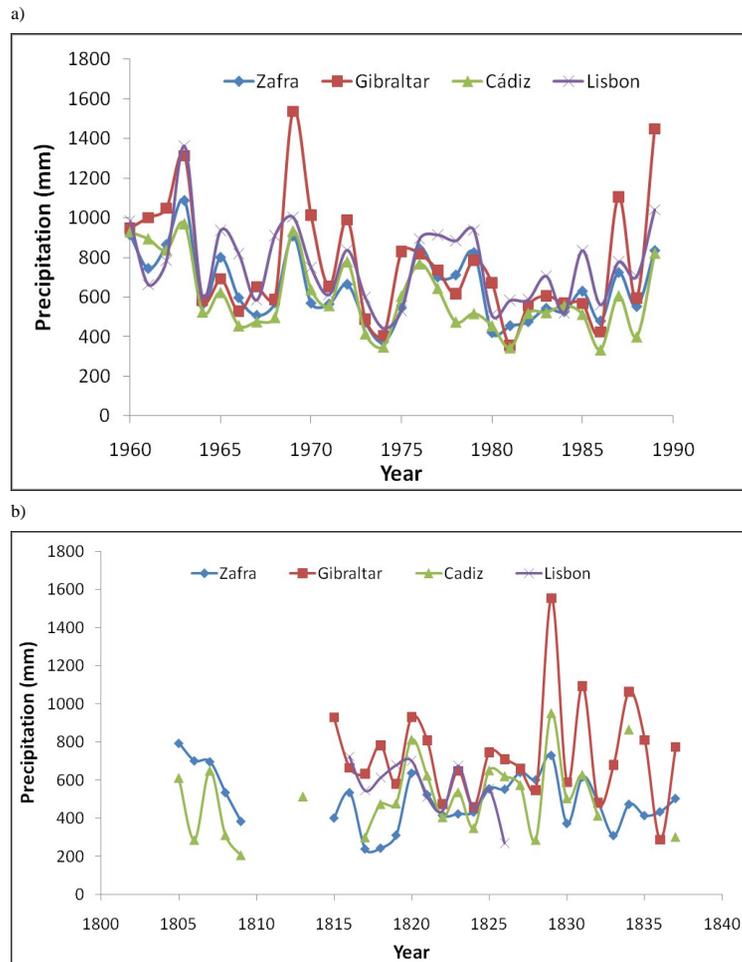


Fig. 6. Rainfall in Zafra, Gibraltar, Cadiz and Lisbon: **(a)** for the period 1960–1990; **(b)** for the period 1815–1840.

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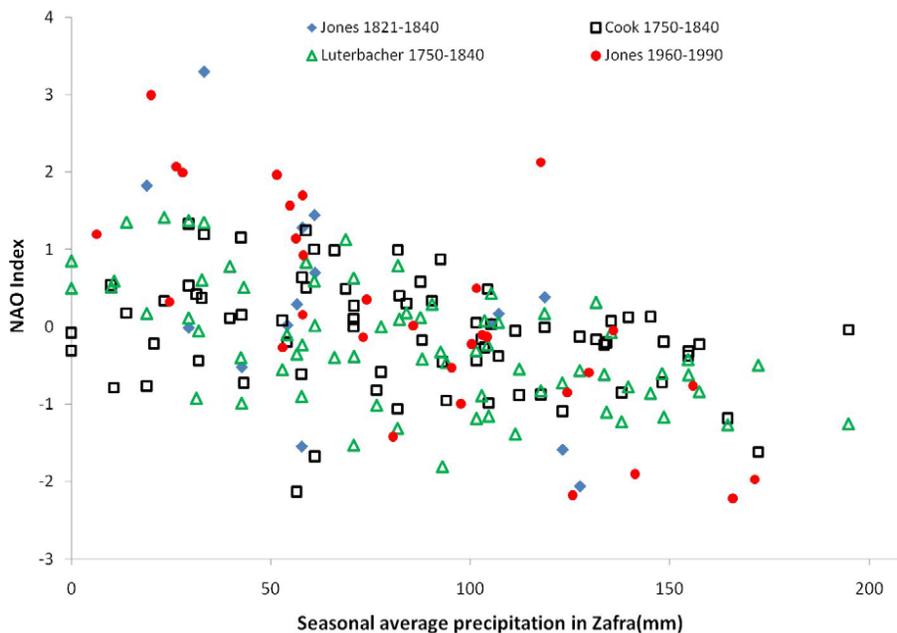


Fig. 7. Relation between the average winter rainfall in Zafra and the NAO index. For details see the text.

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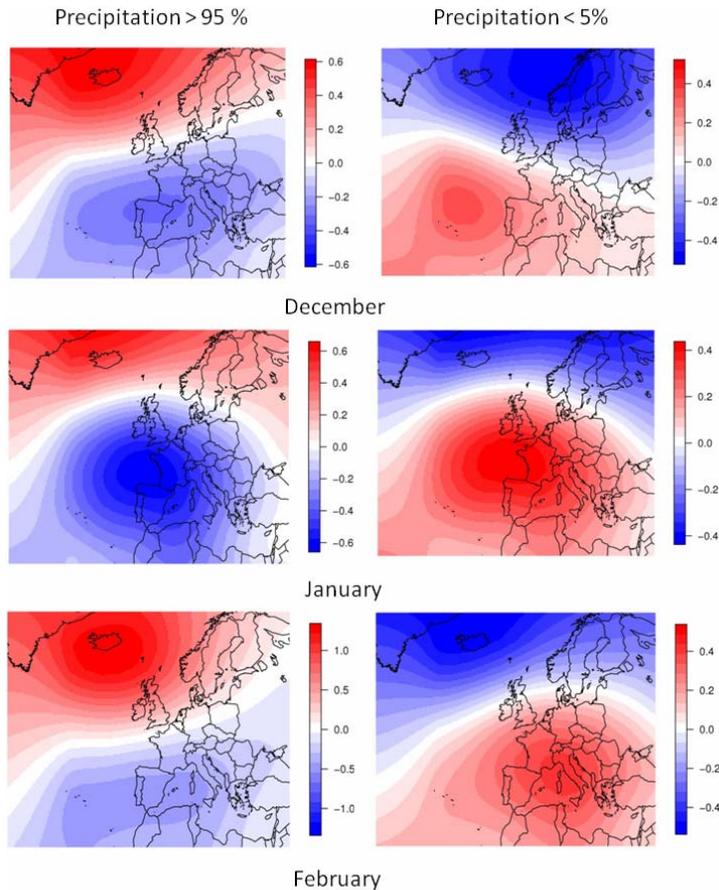


Fig. 8. Maps of average anomalies (%) of Sea Level Pressure for the winter months (December, January and February) in the period 1750–1840: left (right) column shows the maps for the months with rainfall above (below) the 95th (5th) percentile. Note that each map has its own scale.

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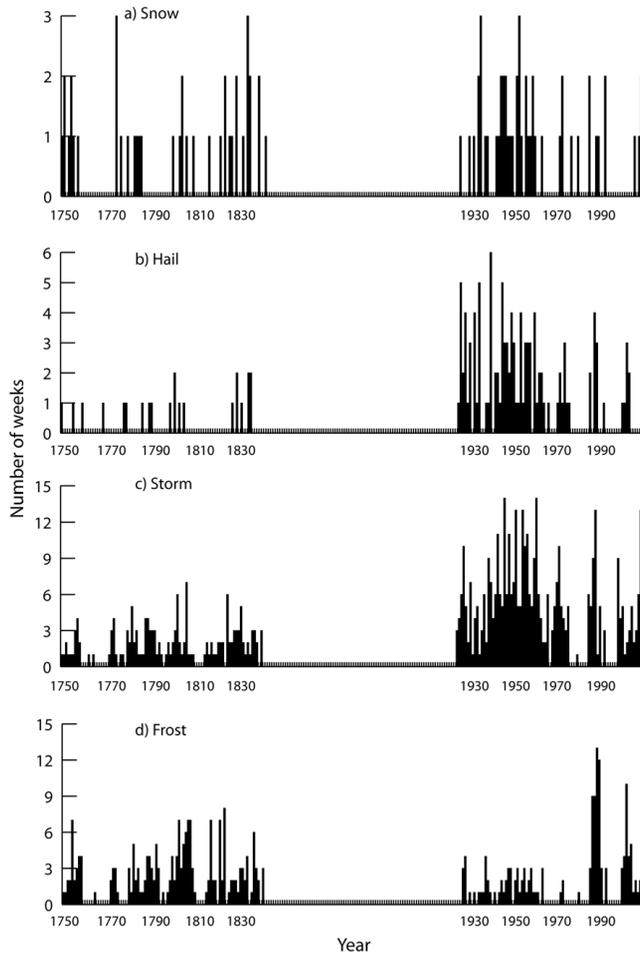


Fig. 9. (a) Number of weeks with snowfall. (b) Number of weeks with hail. (c) Number of weeks with storms. (d) Number of weeks with frost.

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