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Climate of the Past Discussions

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Climate variability in Andalusia (southern Spain) during the period 1701–1850 AD from documentary sources: evaluation and comparison with climate model simulations

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Abstract

In this work, a reconstruction of climatic conditions in Andalusia (southern Iberia Peninsula) during the period 1701–1850, as well as an evaluation of its associated uncertainties, is presented. This period is interesting because it is characterized by a minimum in the solar irradiance (Dalton Minimum, around 1800), as well as intense volcanic activity (for instance, the eruption of the Tambora in 1815), when the increasing atmospheric CO_2 concentrations were of minor importance. The reconstruction is based on the analysis of a wide variety of documentary data. The reconstruction methodology is based on accounting the number of extreme events in past, and inferring mean value and standard deviation using the assumption of normal distribution for the seasonal means of climate variables. This reconstruction methodology is tested within the pseudoreality of a high-resolution paleoclimate simulation performed with the regional climate model MM5 coupled to the global model ECHO-G. Results show that the reconstructions are influenced by the reference period chosen and the threshold values used to define extreme values. This creates uncertainties which are assesed within the context of the climate simulation. An ensemble of reconstructions was obtained using two different reference periods and two pairs of percentiles as threshold values. Results correspond to winter temperature, and winter, spring, and autumn rainfall, and they are compared with simulations of the climate model for the considered period. The comparison of the distribution functions corresponding to 1790–1820 and 1960–1990 periods indicates that during the Dalton Minimum the frequency of dry and warm (wet and cold) winters was lesser (higher) than during the reference period. In spring and autumn it was detected an increase (decrease) in the frequency of wet (dry) seasons. Future research challenges are outlined.

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1 Introduction

Anthropogenic influence on climate overlaps a background of natural climate variability that may diminish or increase it. The lack of instrumental surface temperature and precipitation estimates prior to the mid-nineteenth century underlines the need to reconstruct the history of climate changes from proxies of climate variability derived from the environment itself and from documentary sources (Rutherford et al., 2005). Among proxy data, documentary evidence, that is, noninstrumental man-made sources, deserve special attention, because in general record climatic anomalies and extreme events, such as droughts and floods, making it possible to relate such events to climatic changes.

Last years a great amount of papers have been published using the methodological basis of historical climatology (a complete review may be consulted in Brázdil et al., 2005, 2010a). Several areas of the Iberian Peninsula have been subjects of climatic reconstructions including Catalonia (Barriendos, 1997) and Aragón (Vicente-Serrano and Cuadrat, 2007) to the northeast, Portugal (Alcaforado et al., 2000; Taborda et al., 2004), or Castile, a central region in Spain (Rodrigo et al., 1998; Bullón, 2008; Domínguez-Castro et al., 2008). In addition, various studies coordinating data for the entire Iberian Peninsula have been published, related to flood events on Spanish river basins (Barriendos and Rodrigo, 2006), droughts during the 17th century (Domínguez-Castro et al., 2010), or seasonal and annual rainfall variability from 16th to 20th centuries (Rodrigo and Barriendos, 2008).

Andalusia (southern Spain, around 37° N, Fig. 1) is of unquestionable interest for climate studies as a result of its geographical placing, being influenced by westerlies from the Atlantic Ocean and the Mediterranean Sea. Rain distribution throughout the year is ruled by the Azores High behavior, which may allow Atlantic cyclones and their associated fronts to cross the region from west to east, or, in the opposite, may delay its movement to the south, invading the Iberian Peninsula and producing drought periods. In addition, the development of winter anticyclonic centers over the region, and

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local thunderstorms and convective rainfall provoked in summer and early autumn by thermal lows must be borne in mind. The main disturbances are linked to the jetstream behavior and the polar front. Due to the importance of the polar front dynamics in middle latitudes, the study of this region is of great interest. Previous historical climatology studies on this region analyze the annual (Rodrigo et al., 2000) and winter (Rodrigo, 2008) rainfall variability since the 16th century. In historical climatology it is always possible to find new documentary data that compel to revise the analyses. Therefore, the main objective of this work is to improve the reconstructions of past Andalusian climate, adding new records covering the period from 1701 to 1850. This period is particularly interesting because include the last years of the Maunder Minimum period (until around 1715), and the Dalton Minimum, between approximately 1790 and 1830, a period characterized by a minimum in the solar irradiance and intense volcanic activity, with the Tambora eruption in April 1815 as main event. From a climatic point of view, therefore, the analysis of climatic data during this period is particularly interesting, due to the role of these external forcing factors (Wagner and Zorita, 2005; Trigo et al., 2009). An additional source of information about past climate variability is provided by climate model simulations. The analysis of model response to external forcing, changes in atmosphere and ocean mechanisms contributing to natural climate variability as well of comparisons between model and proxy data help to improve our understanding of past climate variability. Therefore, other important objective of this work is the evaluation of reconstruction method using climate model simulations, and the comparison of climate reconstructions with climate model simulations.

The paper is organized in the following way: data are presented in Sect. 2 (a list of new documentary sources is included in the Appendix), and the reconstruction methodology used is explained in Sect. 3. Section 4 presents the main results, in Sect. 5 these results are compared with other data, and conclusions and challenges for future research are exposed in Sect. 6.

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2 Data

2.1 Documentary data

Andalusian historical weather records were obtained by the rigorous analysis of original documents from a variety of sources: urban annals, city and religious chronicles, brief reports of events, private correspondence, books of acts of church and city archives, medical studies, early newspapers, etc. The criteria followed in analyzing the reliability of sources are time-space closeness to the event, liable transmission of oral or written information, cross-information from different sources, a good agreement among contemporary proxy data such as agricultural production, and the conciseness of authors in describing well known non weather events, e.g. military and political events, plagues, famines, epidemics, eclipses and earthquakes. The advantage of using different kind of sources lies in the fact that allows for an adequate cross-comparison of news collected, assists in eliminating faults and in comparing information from different documents. Consequently, such methodology partially eliminates the subjectivity inherent in this kind of data. Data sources used in previous works (Rodrigo et al., 1999; Rodrigo, 2008) have been enlarged, adding new data sources recently discovered, basically early newspapers and medical studies. From the late years of the 18th century to the first decades of the 19th century, anonymous observers began to send their meteorological observations to local newspapers to ensure that people were informed of them. Instrumental daily meteorological data appear in most of them. Although their spatio-temporal coverage is incomplete, these data sources may complete the description of general climatic conditions, as well as the nature and character of extreme events in past. Empirical research of medical and geographical nature began in Spain in the 18th century with a set of studies that considered the strong influence of climate and environment on the appearance of illness and epidemics. These studies are called "medical topographies", and in many occasions they included meteorological observations made by the physicians. A summary of the new data sources used in this work is shown in the Appendix.

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The processing of compiled reports began by their codification. This allowed the ordering of information in time-space and type (rain, thermal, wind, cloudiness). Most data relates to Seville and the Guadalquivir River Basin (46.4 %), Granada together with Sierra Nevada Mountains (14.0 %), and Málaga on the Mediterranean coast (13.4 %). The majority of data correspond to rain-related phenomena (68 %), basically extreme events, such as continuous and intense rainfalls, floods and droughts, but the 15 % of the records is related to thermal regime (heat and cold waves, frosts, snowfalls) and the 17 % of the records relates to other events as winds and fogs. In the case of temperatures, the subjective appraisals of the authors on the degree of cold or heat were only taken into account when they were associated with more objective observations, such as the ones related to frosts, snowfalls, thunderstorms, etc. News related to frosts, snowfalls, or excessive cold unusual for the considered season (spring, summer) were considered as cold extremes, and news related to heat in months when it is not usual (between November and February), or the convective storm appearance between the end of spring and the beginning of the autumn (May to September) were considered as warm extremes, since these phenomena are related to the relative low-pressure presence of thermal origin in the Iberian Peninsula. When news refers to cold (warm) weather in winter (summer), they were considered as normal. Time resolution depends on the data source, varying from daily (57.6 %) to annual (7 %). For the purposes of this study, a seasonal resolution was chosen, considering the seasons of the year in the usual way, that is, winter = December to February, spring = March to May, summer = June to August, and autumn = September to November. The information varies seasonally, with 36.6 % of the news in winter, 25.4 % in autumn, 22.9 % in spring, and 15.1 % in summer. This distribution is a result of the interest of data sources in everything affecting the state of agriculture and evolution of crops, especially wheat sown in autumn and harvested in early June.

Documentary data collected refer to the period 1701–1850 (from 1851 onwards there are available instrumental data at least with monthly resolution). For the entire period from 1701 to 1850 the average number of records is 3.4 items/year, an information density higher than that from previous studies on this region (Rodrigo et al., 1999). Time coverage of these data is shown in Fig. 2, which shows the number of records per year and decade. It may be seen that the density of information increases notably from 1780s forwards, with important peaks around 1800s, 1820s and 1840s decades. In a preliminary view, these peaks correspond to a highest frequency of extreme events, with winter as the season of the year with more records.

The basic hypothesis is that extreme seasons correspond to situations in which certain threshold values were exceeded. In historical climatology there is always the reservation that this type of data is connected with a huge loss of information compared with instrumental data. Therefore, it is necessary to confirm if the number of events detected is enough to try further analysis. To answer this question we can use the concept of binomial random process (Frei and Schär, 2000). The binomial concept considers the number of events at a particular time as the random process consisting of m independent trials (e.g. total number of seasons in a given period), with probability π for a successful trial, e.g. threshold exceedance. To select the threshold values one must reach a compromise between choosing values high enough to focus on tail behavior of the distribution function and choosing threshold values low enough to ensure that a reasonable number of exceedances occur (Solow, 1999). If the threshold values are the percentiles 10 and 90 (c_{10} and c_{90}, respectively), $\pi = \text{Prob}\{X < c_{10}\} + \text{Prob}\{X > c_{90}\} = 0.20$. These percentiles are commonly used to define the frequency of extreme indices, such as cold nights or warm days, and correspond to moderately extreme events (Zhang et al., 2005). The expected value $\langle n \rangle$ and variance var(n) of the distribution for $m = 31$ are $\langle n \rangle = \pi m = 6.2$, and var($n$) = $m\pi(1-\pi) = 4.96$, respectively. Similar to Briffa et al. (2002) or Pauling et al. (2006), we use ±2 SE to provide an estimate of the uncertainties that are associated with the estimation of the number of extreme seasons. Therefore, we will consider that the total number of extreme seasons is satisfactory when it is included in the interval $\langle n \rangle \pm 2\sqrt{\text{var}(n)} = (1.7, 10.6)$. The total number of extreme seasons seems reasonable in the case of winter temperatures (since around 1780), with an average value of 4.3 extreme seasons for

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each 31 yr period. Mean values of the other seasons of the year are 1.3 for spring, and 1.1 for summer and autumn. In the case of rainfall, the average number of extreme seasons for each 31-yr period are 7.6, 7.4, 4.2, and 7.2 for, respectively, winter, spring, summer, and autumn. In consequence, in the following we will focus our study on winter temperature and seasonal rainfalls, and we will not consider the cases of spring, summer, and autumn temperatures.

2.2 Instrumental data

Instrumental regional series of seasonal temperature and precipitation were obtained from the 19th century to 2005, using the longest available data series in Andalusia (five stations for temperature, since 1851, and nine stations for rainfall, since 1813, see Table 1). These series, in general terms, coincide with the locations of the documentary data in the pre-instrumental period. All the stations are distributed around 36-37° N of latitude, and between 1° and 7° W of longitude, with different heights above sea level (from Málaga at 7 m a.s.l. to Granada at 685 m a.s.l.). Temperature series are from the database SDATS (Spanish Daily Temperature Data, Brunet et al., 2006) and rainfall series were provided by the Spanish Meteorological Agency (AEMET) and the British Meteorological Office in the case of Gibraltar (Wheeler, 2007). All of them are high quality series, without homogeneity problems (Almarza et al., 1996). Local monthly rainfall totals were used to obtain seasonal total rainfall. The regional series was obtained for each season averaging the corresponding local values, and considering in each year the number of stations with data. Table 2 shows the statistics corresponding to the reference period 1960–1990. Basic statistics correspond to Mediterranean climatic characteristics, with wet and mild winters, warm and dry summers, and spring and autumn as transition seasons. A season may be characterized as dry (cold) if total rainfall (average temperature) is lower than the 10th or 25th percentile of the reference period (c_{10} and c_{25}, respectively). Similarly, a season was considered as wet (warm) if total rainfall (average temperature) is higher than the 75th or 90th percentile of the reference period (c_{75} and $c_{90,}$, respectively). The Kolmogorov-Smirnov test (Wilks, 1995)

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was applied to test the normality of the distribution, obtaining that there is not enough evidence to prove that the distribution is not normal, at a 95 % confidence level, except for summer rainfall.

2.3 Simulated climate in Andalusia

A climate simulation has been used to test some aspects of the methodology and evaluate the magnitude of the uncertainties of the methodology, as further discussed in the next section. The simulation covers the Iberian Peninsula with a spatial resolution of 30 km during the period 1001–1990. It was performed with a climate version of the regional model MM5, and was driven through the domain boundaries by a simulation performed with the Global Circulation Model ECHO-G (Zorita et al., 2005). Both simulations consider variations in three main external factors: concentration of Green House Gases, total solar irradiance at the top of the atmosphere and the effect of big volcano events. These factors evolve in the simulation according to the reconstruction by Crowly (2000). This simulation has been proven to simulate realistically many aspects of the climate of the IP in the recent past, where there is reliable data and observations to compare with, and significantly improves the skill of the simulation performed with the global model alone. The reader is referred to Gomez-Navarro et al. (2011) for a technical description and validation of this simulation. This article focuses in the simulated seasonal means of temperature and rainfall regionally averaged over Andalusia.

3 Methodology

The reconstruction methodology used was explained in Rodrigo (2008). The advantages of this method are that avoids possible subjectivity problems (due to the documentary source, or the researcher) associated with the assignment of ordinal indices to quantify documentary data, and it does not need an overlapping period with instrumental data to obtain quantitative estimates of the climate variables in past. Changes

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in the mean value and/or in the standard deviation will yield changes in the probability of extreme events, and, therefore, in the frequency of these events. Our aim is to study the inverse problem, that is, infer changes in mean and standard deviation from the frequency of extreme events, having in mind that documentary data basically reflect the occurrence of extreme events and its impacts. The starting point of the study consists simply in accounting the frequency of extreme seasons in past periods. A season is considered extreme if documentary data inform on the occurrence of extreme events during the corresponding months (heat waves, snowfalls, frosts, intense and/or continuous rainfalls, floods, droughts). The length of the periods considered is 31 yr, which allows the comparison with the modern reference period. In this way, the numbers n_l and n_h of, respectively dry or cold, and wet or warm seasons within a given 31-yr period may be established.

If F_X is the distribution function representative of the climate variable (in our case, seasonal average temperature and rainfall), the quantiles q_l and q_h of the distribution function, corresponding to dry/cold and wet/warm seasons respectively, may be found as

$$\frac{n_\mathrm{l}}{n} = \mathrm{Prob}\{X \le q_\mathrm{l}\} = F_X(q_\mathrm{l}) \longrightarrow q_\mathrm{l} = F_X^{-1}\left(\frac{n_\mathrm{l}}{n}\right)$$
$$\frac{n_\mathrm{h}}{n} = \mathrm{Prob}\{X > q_\mathrm{h}\} = 1 - \mathrm{Prob}\{X \le q_\mathrm{h}\} = 1 - F_X(q_\mathrm{h}) \longrightarrow q_\mathrm{h} = F_X^{-1}\left(1 - \frac{n_\mathrm{h}}{n}\right) \quad (1)$$

where n is the total number of seasons in the chosen period (in our case, $n = 31$).

The following step is to choose an appropriate distribution function to represent the data. The more simple election is the normal distribution function, having in mind that the regional series of temperature and precipitation are obtained as the average value of the individual series. At the time scales in which we are working, the precipitation amounts tends to be more closely approximating to the normal distribution, because of the central limit theorem, which states that under fairly general conditions, the sum of independent variables approaches normal (Lettenmaier, 1995). This hypothesis, in the case of Andalusian rainfall, is valid for all the seasons of the year, except summer

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(Rodrigo, 2002), and it was tested for the instrumental regional series of the reference period (Table 2). The normal distribution may be standardized and transform in a normal distribution of mean 0 and standard deviation 1, $N(0;1)$. Therefore, as basic hypothesis, we establish that $F_X = N(0;1)$. The quantiles of the series may be established using $c = u + sq$, where u is the mean value, s the standard deviation, and q the quantile of the $N(0;1)$. Therefore,

$$c_l = u + sq_l \; c_h = u + sq_h \tag{2}$$

If we know the values of the c quantiles, then we have two equations system, with 2 unknown variables, u and s. Mean value u and standard deviation s of a given period may be found as

$$s = \frac{c_h - c_l}{q_h - q_l}$$
$$u = c_h - sq_h = c_l - sq_l \tag{3}$$

The application of this method is only possible if we have enough data to accomplish the different steps. In fact, if $n_l = 0$, then $q_l \to -\infty$, and if $n_h = 0$, then $q_h \to \infty$. Therefore, the absence of information on extremes in certain periods imply the appearance of gaps in the reconstructed series.

Summarizing, for each 31-yr period, from documentary data analysis, n_l and n_h are accounted. These numbers are used to estimate q_l and q_h, and the s and u values are estimated considering the values of c_l and c_h corresponding to the reference period. Therefore, the basic hypothesis is that we can consider that past extreme events may be defined in a similar way to present, that is, we assume that threshold values of the reference period were exceeded when there was an extreme event in past.

This methodology can be tested within the context of the pseudoreality of the climate simulation. The underlying idea is that even if the evolution of the simulation does not match perfectly the actual evolution of the climate in the past millennium, it represents a feasible evolution of the climate, since it is physically self-consistent. Thus, the statistical properties of the simulated variables, and their physical relationships, are a

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reliable version of the actual ones. An obvious advantage of using a climate model is that within the simulation the information is available at all temporal and spatial scales. Thus, one can construct a pseudoproxy inside the model for a given variable, apply the reconstruction methodology to be tested and generate a pseudoreconstruction. It can be later compared with the simulated evolution of the variable, which is perfectly known. It is important to note that this exercise does not validate the model, but the methodology used to reconstruct the actual climate.

The procedure to create the pseudoproxy is as follows. A reference period has to be chosen, as well as a probability threshold to define what an extreme event is. Once this is fixed, the c_h and c_l values can be found. The next step is to compare the simulated seasonal means with these percentiles, to get a series of 0's and 1's representing the occurrence or not of an extreme season. Using a running window of 31 yr, the number of extreme seasons in a given period, n_l and n_h, can be accounted, which are the pseudoproxy.

An important drawback applying the above methodology is that a reference period, as well as a probability threshold to define an event extreme, has to be arbitrary defined. The reconstruction methodology is in principle sensible to this choice, introducing an uncertainty factor which is important to assess. Four different combinations have been tested in the present study: two reference periods (the 31-yr periods 1885–1915 and 1960–1990) with two pairs of probability thresholds (percentiles 10–90 and 25–75), receptively. This exercise has been applied to the simulated winter mean series of temperature and precipitation (the results for other seasons are similar, and are not shown) to reconstruct the simulated evolution of these variables during the last millennium.

Figure 3 represents the evolution of the 31-yr running mean of temperature and precipitation in the simulation, together with the four tested pseudoreconstructions. The black line in the upper (lower) panels represents the running mean of the evolution of temperature (precipitation). For each variable, two periods have been used as reference (1885–1915 and 1960–1990), as well as two sets of percentiles (10–90 and

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25–75, in red and blue, respectively). Overall there is a very good agreement between the original and reconstructed series, although it is slightly better when the larger percentiles are used. This is a statistical problem linked to the ability of a sample of only 31 elements to sample the tails of the normal distribution. More importantly, there are several gaps in the pseudoreconstructions, happening when no extreme events are registered in the window, as discussed above. The gaps are specially noticeable in temperature and when the period 1960–1990 is used as reference. This is again a sampling problem, due to the large differences between the mean temperatures in this warm reference period and other colder periods of the past in the simulation. Similarly, Fig. 4 represents the same as Fig. 3 for the reconstructions of standard deviation. In this case the agreement is worse, although the magnitude order is correct. As before, there are some gaps, specially in temperature when the 1960–1990 period is chosen as reference.

A measure of the agreement between the original series and the reconstructions is the Root Mean Square Error (RMSE). It varies among the four tested reconstructions, ranking from 0.08 to 2.3 °C in mean temperature, and from 9.0 to 15.2 mm in mean precipitation. Similarly, the standard deviation reconstructions vary from 0.1 to 0.2 °C and from 13.8 to 21.0 mm in temperature and precipitation, respectively. However, there is no a clear relationship between a lower RMSE and the chosen period or percentile. The mean value of the RMSE in the four pseudoreconstructions can be considered as a measure of the uncertainty in the methodology due to the arbitrary choice of the references, and it is hereafter used as the uncertainty bar when reconstructing the actual climate.

4 Reconstruction

The methodology explained in the previous section was applied to the number of extreme seasons observed in documentary data for winter temperature and winter, spring and autumn rainfall (normality hypothesis is not valid for summer rainfall). The

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procedure was applied to consecutive periods with a running window of 31 yr, the first one being 1774–1804, the second one 1775–1805, until the last 31-yr period 1820–1850 for temperature (1701–1731, 1702–1732,. . . ,1820–1850 for rainfall). Therefore, the reconstruction yields the 31-yr running means and standard deviations. Four reconstructions were initially made, using two reference periods, and two pair of threshold values c. The reference periods chosen were 1885–1915 and 1960–1990. For each variable, t-test for difference between means, F-test for variances ratio, and Kolmogorov-Smirnov test were performed to compare periods. The period 1885–1915 was significantly cooler in winter and wetter in spring and autumn (Table 3). For each reference period, two reconstructions were made, using as threshold values c_l and c_h the percentiles 10 and 90, and 25 and 75, respectively. Table 3 shows that these values may be very different, although there are not significant differences between periods (as for instance in the case of winter rainfall). The definitive reconstruction was obtained as the ensemble of the four individual reconstructions, and the associated uncertainty was estimated from the model simulations.

The methodology allows reconstruct low-frequency changes in the climate variables. Nevertheless, as it will be seen below, it is possible to obtain high-frequency variability (interannual time-scale) when there is not gaps between reconstructed and instrumental series.

Figure 5 shows the results corresponding to winter temperature for mean value u (top) and standard deviation s (bottom), with the uncertainties bands determined by the RMSE within the model. Blue horizontal continuous lines indicate the value corresponding to the reference period 1960–1990. First, it may be seen that mean temperatures were slightly lower (up to 0.5 °C) than the modern value, with a minimum around the periods centered in 1815 and 1820. In second place, variability of winter temperatures is slightly lower than that of the reference period, although slightly increases with a peak around the same time interval, and at the end of the reconstructed period. The last result may be yielded by the increasing number of observations at the end of the record.

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Figures 6 to 8 show the reconstructions for winter, spring, and autumn rainfall, respectively. In these cases, there is an overlapping period with instrumental data (green line) but the overlapping period is very brief to try obtain statistical correlations. In all the cases, standard deviation reconstructed is lower than that of the reference period 1960–990, except at the end of the series, probably as consequence of the loss of variance in proxy data when comparing with instrumental data. In the case of winter rainfall, mean value was higher than during the reference period 1960–1990. The reconstructed values show minima around 1750, 1770, and 1790, an increase of rainfall in the first decades of the 19th century, and decreasing rainfalls at the end of the series. Comparison with instrumental running means at the end of the record shows that the magnitude of reconstructions is similar to instrumental values. In this case it must be in mind that instrumental values correspond mainly to Gibraltar, that it is noticeably wetter than nearby sites in mainland Spain (Wheeler, 2007).

Figure 7 shows the reconstruction corresponding to spring rainfall. The gap corresponding to the first years of the 19th century is due to the absence of information on droughts ($n_l = 0$) from 1790 to 1824. Results show a dry period approximately between 1730 and 1790, with an increase of spring rainfall in the last decade of the 18th century and first decades of the 19th century. Comparison with instrumental running means shows that reconstruction slightly overestimates the instrumental values.

Figure 8 shows the reconstruction corresponding to autumn rainfall. The gap corresponds to the absence of information on droughts from 1782 to 1826 ($n_l = 0$). Nevertheless, the behavior of autumn rainfall is very similar to spring rainfall, with a minimum in the period centered around the 1760s decade, and progressive increase of precipitation from 1790s onwards. Again the reconstruction clearly overestimates instrumental values. A possible explanation lies in the character of rainfall during this season of the year, with an important role of convective precipitation, that is, intense, of short duration, and local rainfalls. In consequence, it may be the result of assigning a extreme character to the seasonal regional series when the event was strictly local, and limited to a few hours a day. A possible solution to this problem would be to refine the

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spatiotemporal resolution of the study, at least at monthly time scale and for individual localities.

5 Discussion

The best proof to confirm these results is to see if there is other evidence showing similar characteristics, from different data sources, corresponding to other proxy data or data from neighbouring regions. Thus far, scarce works have attempted to reconstruct the evolution of temperatures over time in the Iberian Peninsula, due to the scarcity of information, except the works by Rodrigo et al. (1998) and Bullón (2008) focused on Castile, in the central area of the Iberian Peninsula, and during brief time periods (1634–1648, and 1550–1599, respectively). Most notorious events during the period analyzed were the occurrence of snowfalls and frosts in localities where these events are very rare, as Cádiz (frosts in the dawn on 10 to 12 February 1803, snowfalls on 12 January 1820), Mediterranean coast (snowfalls in Motril on 19 January 1816, frosts in Almuñecar on 10–11 January 1830, frost in Málaga on 12 January 1850), and Seville (frosts on February 1822, 1823, and December 1846, snowfalls on 7 February 1819 and February 1845). Some works have studied early instrumental data in Cádiz and they allow obtain a first approach on the evolution of temperature in the region. In relation to winter temperature, Wheeler (1995) found that winter temperatures of Cádiz from 1789 to 1816 were about 0.6 °C lower than modern data, a result very similar to our reconstruction. Gallego et al. (2007) found that sunset temperatures taken in Cádiz for 1825–1852 show values up to 2.7 °C lower relative to the 1971–2000 period from December to February. On the other hand, although it seems that impacts of the Tambora eruption on Iberia were more important in summer (Trigo et al., 2009), it has been detected a minimum in winter temperature precisely around 1815–1820. The analysis of early instrumental data in the region is a work in progress, but the first results seem confirm, at least qualitatively, the validity of our reconstruction.

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The organization by the municipal and ecclesiastic authorities of religious ceremonies (rogations) when a climatic factor altered the usual development of the principal crops allows the reconstruction of the variations of precipitation, the principal conditioning factor of the cereal production in the Mediterranean climate (Martin-Vide and Barriendos, 1995). The compilation of series of *pro serenitate* (excess of precipitation that produced flooding) and *pro pluvia* (droughts) rogations has allowed reconstruct rainfall fluctuations (Rodrigo and Barriendos, 2008), and time series of floods (Barriendos and Rodrigo, 2006) and droughts (Domínguez-Castro et al., 2010) in the Iberian Peninsula. The conversion of this information to monthly climatic indices assigns an ordinal index to the months with rogations information (+1 to *pro serenitate,* −1 to *pro pluvia* rogations, 0 to lack of information or absence of extreme events). Seasonal indices are obtained as the sum of the corresponding monthly indices, ranging from −3 to +3. The rogation series corresponding to Seville has not used in our reconstruction, it has reserved to compare with our results. In comparing, we must take into account that rogation series is local, meanwhile our reconstruction is regional. The methodology used reconstructs 31-yr running means, not annual values. Therefore, we must convert the mean values obtained into annual values. Running means may be expressed as

$$u_t = \frac{1}{2r+1} \sum_{k=-r}^{k=r} x_{t+k} \tag{4}$$

where x is the annual value, and $2r+1 = n$ ($n = 31$, $r = 15$ in our case). In consequence, considering two consecutive running means, we obtain that

$$x_{t-r} = x_{t+r+1} - n(u_{t+1} - u_t) \tag{5}$$

In this way, it is possible to obtain past annual values by means of an iterative process, from instrumental values and running means. An inconvenient of this method is that the presence of gaps (in instrumental series or running means) propagates backward preventing a complete reconstruction. This methodology was used for the rainfall winter and spring time series (the number of gaps in autumn was very high) considering that

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instrumental series begins in 1821, and the first instrumental running mean is centered in 1836. Therefore, annual values were obtained from 1820 to 1701. Figure 9 shows the comparison of the annual values obtained (z, expressed as standardized anomalies relative to the reference period 1960–1990) with the index series from rogations in Seville (I) for winter (a) and spring (b) during the same time period. Correlation coefficients are significant at the 95 % confidence level, but not very high ($r = 0.30$), due to various factors: I series are local, meanwhile z series are regional; the existence of gaps in the instrumental series (1833, 1834, 1836, and 1837 in winter; 1824, 1825, 1833, 1836, and 1837 in spring) and the u series for spring (1805–1809, Fig. 7) multiply the number of gaps in past (in total, 16 (13.3 %) in winter and 34 (28.3 %) in spring), and the absence of information on rogations led to assign an index value I = 0 in years in which the reconstruction shows positive and negative anomalies (for instance at the beginning of the 18th century in spring). However, at least from a qualitative point of view, the coincidence of positive and negative values is clear. Common positive values are detected for example in 1708, 1768, 1784, or 1808 (winter), and 1736, 1772, 1786 and 1804 (spring). Common droughts are found in 1737, 1753, 1789, and 1808 (winter), and 1722, 1737, 1750, 1780, and 1813 (spring).

Rogation ceremonies and rainfall information contained in documentary data are directly related to the behavior of crops, mainly wheat and barley. There is other important data source related to the agricultural production: the harvest taxes, or *tithes*. Every producer or owner had to pay 10 % of the total production either in kind or in money, after a public auction. This proxy has been used to reconstruct the precipitation in the Canary Islands for the period 1595–1836 (García et al., 2003). In Andalusia there is available a great number of tithes series after the compilation by Ponsot (1986), based on municipal and ecclesiastical archives of the Guadalquivir River Basin. For this work, we have used 22 series covering the period 1580–1837. The magnitude of tithes were very different from one locality to another, depending of the extension of the farm area, thus the local series were standardized using the mean value and standard deviation of the complete period. The next step was to construct a cereal production

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index I_c averaging the local indices. Figure 10 shows the evolution of I_c from 1701 to 1820. In interpreting, we must have in mind that cereal production not only was related to climatic factors, but also to socioeconomic factors (agricultural techniques, political conflicts). In addition, the response of the plants to climate is not linear, it depends on the different stages in the evolution of the plant, and it is related not only to precipitation, but also to the appearance of frosts, heat waves, etc. However, a qualitative comparison is possible, considering that $I_c \leq -1$ ($\geq +1$) indicates poor (good) harvests in the region. Results are summarized in Table 4, showing the years with $|I_c| \geq 1$ and the corresponding values of the reconstructed rainfall anomalies z_w and z_{sp} for winter and spring, respectively. Poor harvests ($I_c \leq -1$) are mainly related to drought conditions, mainly in spring, with droughts in the decades of 1730s and 1750s, but intense and/or continuous rainfalls may also affect the crops, as in 1784, 1804, and 1812. In particular, the winter 1783/1784, with a severe flood in Seville, has been considered as typical for the Little Ice Age across much of Europe (Brázdil et al., 2010b) and a flood in Granada was recorded on 9 May 1804. Good harvests seem related to rainy seasons or negative anomalies not very pronounced, as in 1746, 1782 or 1808.

An interesting exercise may be the comparison between the Dalton Minimum period (approximately 1790–1820) and the reference period 1960–1990. Figure 11 shows the density function corresponding to both periods, accepting the normality hypothesis, for winter temperature (a) and precipitation (b) continuous blue line represents the density function of instrumental data for the period 1960–1990, and red continuous line the reconstructed data for 1790–1820. Dashed lines represent the density functions obtained from model simulations. The mean (standard deviation) temperature for the Dalton minimum is 10.6 (0.5) and 8.3 (0.8) °C in the reconstruction and the model, respectively, whereas the values for the 1960–1990 periods are 11.0 (0.8) and 9.3 (0.6) °C. Similarly, mean (standard deviation) rainfall for the Dalton minimum is 233 (59) and 200 (90) mm whereas the values for the 1960–1990 periods are 224 (111) and 180 (95) mm. Hence, a first result is that the variance of reconstructed data is clearly lower than the instrumental data, which is attributable to the loss of variance inherent to

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the use of proxy data. In second place, model simulations clearly underestimate instrumental and reconstructed data (especially in the case of temperature). These bias are within the range of uncertainty characteristic of regional climate simulation, specially when the simulations are not externally driven by observations, as is the case. However, the simulation does not show such a large bias when it is compared against other available observational data bases (Gómez-Navarro et al., 2011), which suggests that a complementary explanation for these biases is the presence of deficiencies also in the instrumental data employed in this study. Nevertheless, more important than biases, which are to a great extent inherent to all models, is the amplitude of climate variations in different climatic periods. In this respect it may be seen that both, reconstructed and simulated climate, show that the period 1790–1820 was colder and slightly wetter than the modern period 1960–1990. In the case of the model this behavior is driven by the reconstructions of the external forcings, which show a decrease in the solar constant together with an increase of volcano activity during this period. Thus, the temperature and rainfall reconstruction for Andalusia presented in this study are in a qualitative good agreement with the Crowley (2000) reconstructions for global-scale forcings.

The increase of rainfall in the first half of the 19th century (or, alternatively, the decrease in the frequency of droughts) coincides with an increase in the frequency of floods in the Tagus river (central part of the Iberian Peninsula, to the north of Andalusia) from 1780 to 1810 (Benito et al., 2003), and in Catalonia (NE Iberian Peninsula) from 1830 to 1860 (Barriendos and Llasat, 2003). From dendroclimatic studies in Spain, Creus Novau (2000) found that the most important effect of the Little Ice Age in Spain was an increase of precipitation, with the tree ring index showing increasing rainfall in the mid-19th century. For Greece, the period 1750–1820 was one of the wettest of the Little Ice Age (Xoplaki et al., 2001). Precipitation anomalies over southern Spain are associated with pressure anomalies over the Atlantic Ocean northwest of the Iberian Peninsula (Xoplaki et al., 2004; Pauling et al., 2006): negative pressure anomaly facilities advection of moist air from the Atlantic and the low triggers precipitation over

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the region; in the case of dry anomalies, this area is dominated by high pressure, which suppresses precipitation because anomalous easterly winds over southern Europe prevent moist oceanic air from reaching southern Spain. Winter precipitation over southern and central Spain is mainly determined by the state of the North Atlantic Oscillation (NAO). In a study on the impacts of the NAO on Spanish rainfall during the 20th century (Muñoz-Díaz and Rodrigo, 2004) was found that changes in NAO phases lead to changes in mean rainfall over this area, with important shifts in the probabilities of wet and dry seasons. This direct relation between mean rainfall over the study area and NAO has been used for SLP and NAO reconstructions (Luterbacher et al., 1999, 2002a, b; Rodrigo et al., 2001). In general terms, results presented in this work are coherent with the monthly reconstruction of the SLP field from independent sources (Luterbacher et al., 2002b): greater meridionality in the general circulation, with more frequent cyclonic disturbances and northerly flows, responsible of the wet and cold events detected, respectively.

6 Conclusions

The study presented here clearly shows the potentially of using documentary data in climatic reconstructions, at least with seasonal resolution. In addition, it is an example of the use of regional model simulations to test reconstruction methodologies and results. Among the main results it can be mentioned the reconstruction of winter temperature, a task that rarely appears in historical climatology studies focused on the Iberian Peninsula. Winter mean temperature was slightly lower than the modern value, with a minimum around the period between 1815 and 1820. In relation to rainfall, it has been detected an increase of mean rainfall since the last decades of the 18th century. The comparison between the periods 1790–1820 and 1960–1990 indicates that the period 1790–1820, that is, the central interval of the Dalton Minimum period, was colder and wetter than the modern period. These results are in good agreement, at

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least from a qualitative point of view, with other reconstructions, from other proxy data and regions.

The application of the method is only possible if a sufficient number of events are recorded in the data base. In this sense, it is affected by the general problem of historical climatology, that is, a huge loss of information compared with instrumental data. The main problem of the methodology is the appearance of gaps when information on extreme events is absent. The lack of this information may be due to incomplete documentary sources or to a real absence of extremes. Traditional reconstruction techniques based on ordinal severity indices, assign the value $I = 0$ to these situations. In this sense, the method followed here is more cautious, waiting for the analysis of new data sources before attempting reconstruction process for periods with lack of news. Some features may be revised, as for instance, the choice of different reference periods, threshold values, or an adequate theoretical distribution function, instead of the normal distribution. All these aspects, along with a deeper analysis of possible relationships with climate forcings, will be studied in future works.

Appendix A

Documentary data sources

Data sources used in this work enlarge the list quoted in Rodrigo et al. (1999) with these new references:

Medical tographies

Delgado, F.: Lección histórico politico médica de las enfermedades que pueden seguirse de resultas de la pasada inundación del Guadalquivir, in: Memorias Académicas de la Real Sociedad de Medicina y demás ciencias de Sevilla, 3, 58–77, 1785.

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Martínez y Montes, V.: Topografía médica de la ciudad de Málaga, Biblioteca de Andalucía, sgn.: 1-N-965, 1852.

Newspapers

Semanario de Agricultura y Artes dirigido a los Párrocos: Biblioteca de la Universidad de Granada, sgn.: B-81-31 to B-81-52, 1797–1808.

Diario Mercantil de Cádiz: Biblioteca Provincial de Cádiz, sgn.: FL-PP-Est.99, 1802–1812, 1816–1830.

El Publicista, Diario de Granada: Museo Casa de los Tiros, Granada, 1812–1813.

Diario del Gobierno de Sevilla: Biblioteca Nacional, Madrid, sgn.: R/60312(4)0269, 1812–1813.

Diario Constitucional de Granada: Museo Casa de los Tiros, Granada, 1820.

Periódico de la Sociedad Médico Quirúrgica de Cádiz: Biblioteca de la Universidad Complutense, Madrid, sgn.: BH MED Rev. 63, 1820–1822, 1824.

Diario de Sevilla: Biblioteca Nacional de Madrid, sgn.: sala PP, 1826–1831.

Diario de Sevilla de Comercio, Artes, y Literatura: Biblioteca de Andalucía, sgn.: P-ANT-8/1, 1829–1830.

El Indispensable de Cádiz:Biblioteca Nacional de Madrid, sgn.: ZR/784(10), 1838.

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Other sources

Anonymous: Nueva y tragica relación... en la Bahía de Cádiz en el espantoso Huracán, que se padeció los días 15 y 16 de Enero de este año de 1752, Biblioteca Provincial de Cádiz, sgn.: BBH6C25-10, 1752.

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Table 1. Meteorological stations in Andalusia (height expressed in meters above sea level; Period *T* = period of daily instrumental observations of temperature; Period *R*: idem for monthly rainfall).

Station	Longitude	Latitude	Height	Period *T*	Period *R*
Almería	01°23′ W	36°51′ N	20		1908–2005
Cádiz/SFdo	06°20′ W	36°45′ N	12	1851–2005	1821–2005
Córdoba	04°51′ W	37°51′ N	92		1894–2005
Gibraltar	05°21′ W	36°08′ N	8		1813–2005
Granada	03°37′ W	37°08′ N	685	1893–2005	1898–2005
Huelva	06°56′ W	37°15′ N	26	1903–2005	1903–2005
Jaén	03°48′ W	37°48′ N	484		1867–2005
Málaga	04°29′ W	36°40′ N	7	1893–2005	1878–2005
Sevilla	05°53′ W	37°25′ N	31	1893–2005	1865–2005

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Table 2. Main statistics of the seasonal regional series for temperature (T in °C) and precipitation (R in mm) for the reference period 1960–1990 (u = mean value; s = standard deviation; c_i = i-th percentile; KS = Kolmogorov-Smirnov statistic, in bold if the fit to a normal distribution is significant at the 95 % confidence level KS < 0.161).

Parameter	Winter	Spring	Summer	Autumn
$u(T)$	11.0	15.5	23.9	18.5
$s(T)$	0.8	0.8	0.7	1.0
$c_{10}(T)$	10.0	14.6	23.1	17.3
$c_{25}(T)$	10.4	15.0	23.7	17.8
$c_{75}(T)$	11.6	16.1	24.3	18.9
$c_{90}(T)$	12.0	16.6	24.6	19.8
KS(T)	**0.078**	**0.088**	**0.149**	**0.106**
$u(R)$	224.2	128.8	22.8	162.3
$s(R)$	111.1	56.8	12.3	86.4
$c_{10}(R)$	111.0	70.4	10.3	56.9
$c_{25}(R)$	147.1	87.1	14.1	87.0
$c_{75}(R)$	271.1	155.3	24.9	212.7
$c_{90}(R)$	381.5	197.0	37.6	263.5
KS(R)	**0.124**	**0.118**	0.182	**0.106**

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Table 3. Main statistics of the reference period 1885-1915 (Twi = winter temperature (°C); Rwi = winter rainfall (mm); Rsp = spring rainfall (mm); Rau = autumn rainfall (mm); u = mean value; s = standard-deviation; ci = i-th percentile) and comparison with the period 1960-1990 (t-test, in parenthesis confidence interval for difference between means; F-test, in parenthesis confidence interval for variances ratio; KS = Kolmogorov-Smirnov statistic, in black differences significant at the 95 % confidence level).

1885–1915				
	Twi	Rwi	Rsp	Rau
u	10.6	228.3	190.1	210.9
s	0.7	102.7	75.9	70.4
c_{10}	9.8	121.9	88.4	126.8
c_{25}	9.9	154.4	132.2	174.9
c_{75}	11.1	289.7	239.4	248.3
c_{90}	11.5	332.4	282.2	299.0
Comparison between 1885–1915 and 1960–1990				
	Twi	Rwi	Rsp	Rau
t-test	**2.45 (0.09, 0.887)**	−0.16 (−58.5, 50.3)	**−3.60 (−95.3, −27.2)**	**−2.43 (−88.6, −8.5)**
F-test	1.10 (0.5, 2.3)	1.17 (0.56, 2.43)	0.56 (0.27, 1.16)	1.51 (0.72, 3.13)
KS	0.2581	0.0968	**0.4194**	**0.3871**

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Table 4. Comparison between reconstructed standardized rainfall anomalies of winter (z_w) and spring (z_{sp}) and cereal production index (I_c), period 1701–1820.

$I_c \leq -1$			$I_c \geq +1$		
Year	z_w	z_{sp}	Year	z_w	z_{sp}
1734	−2.0	−8.8	1709	−2.0	Gap
1737	−0.8	−2.3	1719	−0.3	−0.8
1750	−0.3	−2.3	1725	+0.2	+3.1
1753	−2.0	−2.3	1735	+3.2	+1.2
1784	+0.1	−0.1	1741	−2.0	+4.3
1804	+0.3	+1.3	1746	−1.6	−0.4
1811	−1.1	−1.2	1755	−2.0	+2.7
1812	+0.2	+0.6	1766	+3.2	+1.2
			1781	−2.0	−2.3
			1782	−0.9	−1.2
			1790	+0.6	Gap
			1794	−1.4	Gap
			1798	+2.8	+1.0
			1802	−2.0	Gap
			1808	−1.6	−0.4

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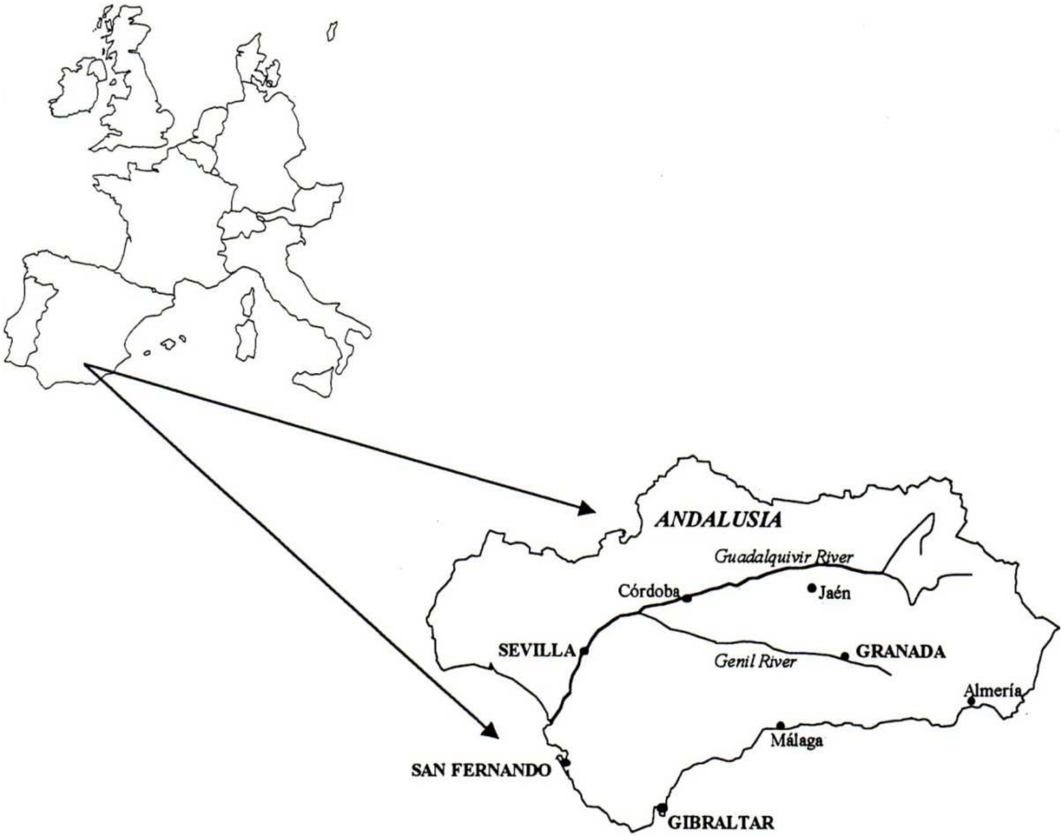

Fig. 1. Map of the study region. Main cities with data are indicated.

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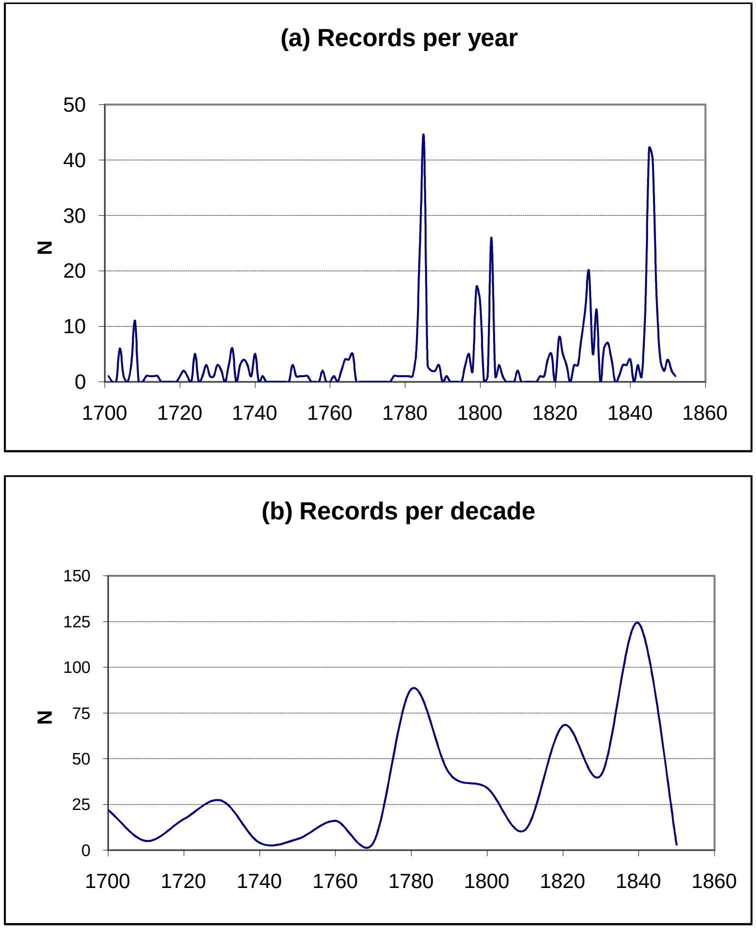

Fig. 2. Number of records from documentary sources, **(a)** by year, **(b)** by decade, during the period 1701–1850.

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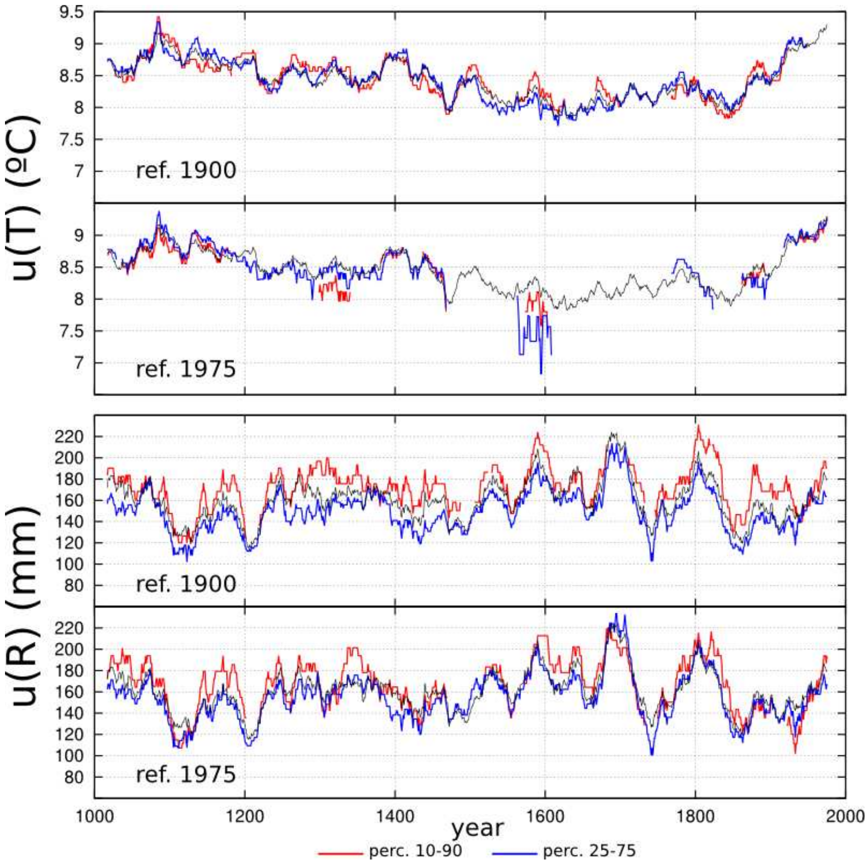

Fig. 3. Evolution (in black) of the 31-yr running mean of temperature (two upper panels) and precipitation (two lower panels) in the climate simulation for the last millennium. Four pseudoreconstructions are shown, using the periods 1885–1925 (first panel and third panels) and 1960–1990 (second and fourth panels) using the 10–90 percentiles (red lines) and 25–75 (blue lines).

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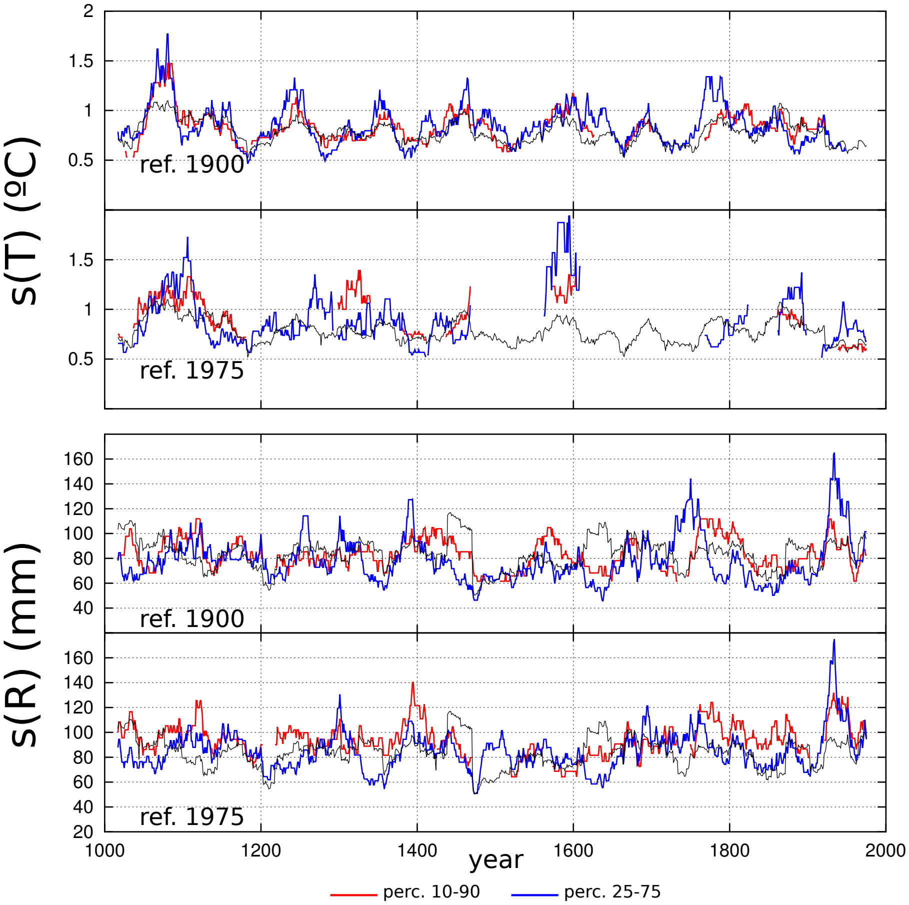

Fig. 4. As Fig. 3 for standard deviation.

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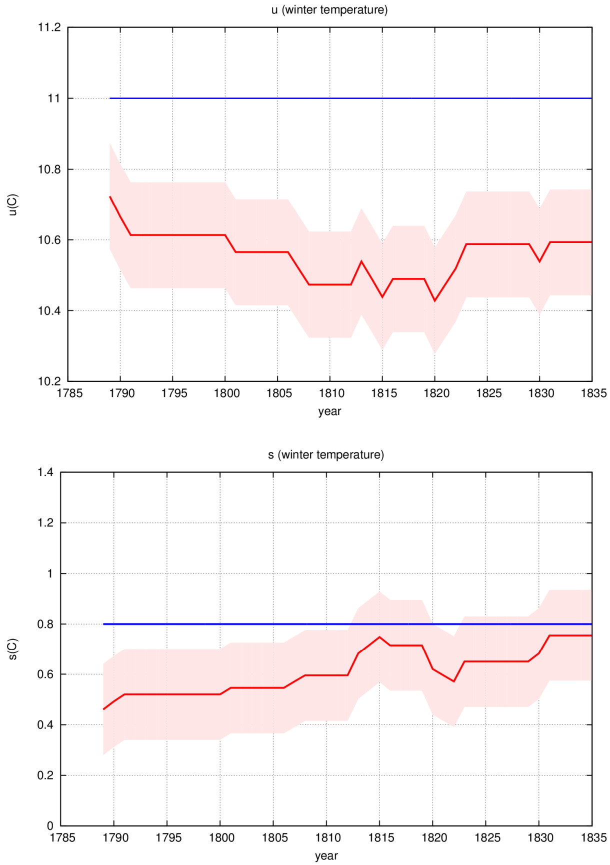

Fig. 5. Reconstruction of mean value (top), and standard deviation (bottom) of winter temperature for 31-yr running periods. The shadow bar represents the uncertainty range estimated using the model simulations for the whole millennium. Blue horizontal line: value corresponding to the reference period 1960–1990.

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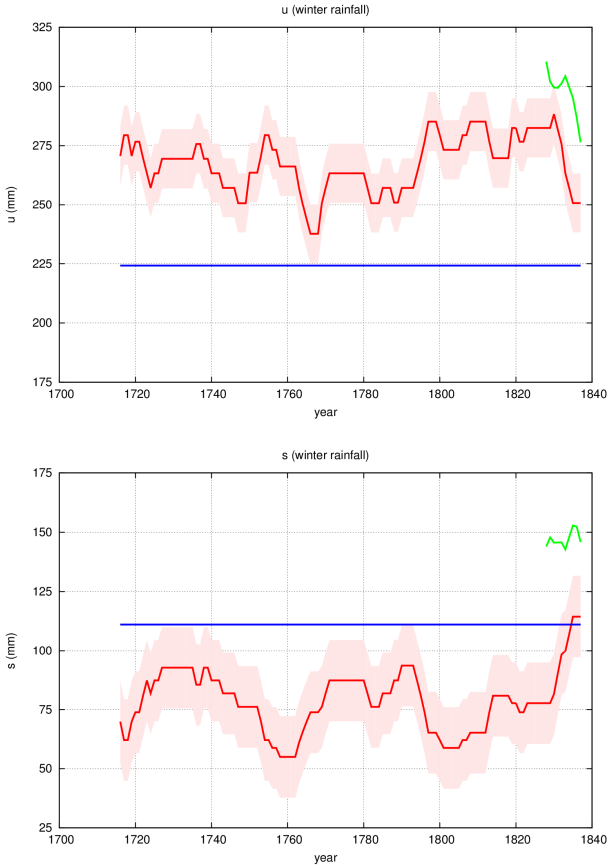

Fig. 6. As Fig. 5, for winter rainfall (green line: instrumental running means).

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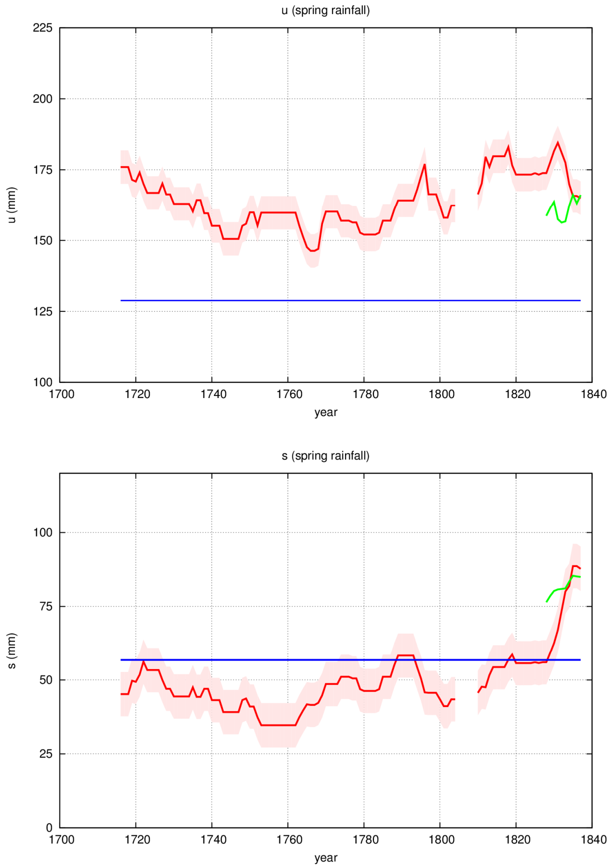

Fig. 7. As Fig. 6 for spring rainfall.

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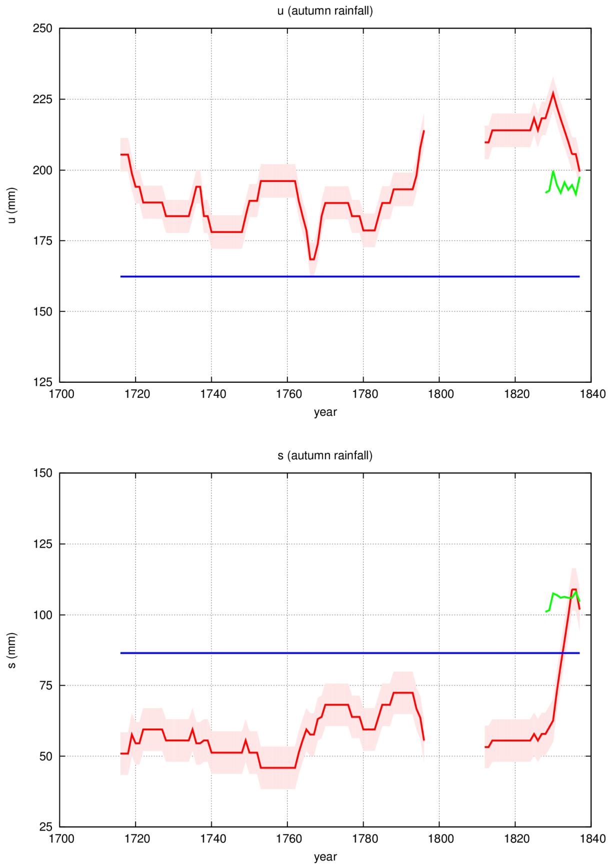

Fig. 8. As Fig. 6 for autumn rainfall.

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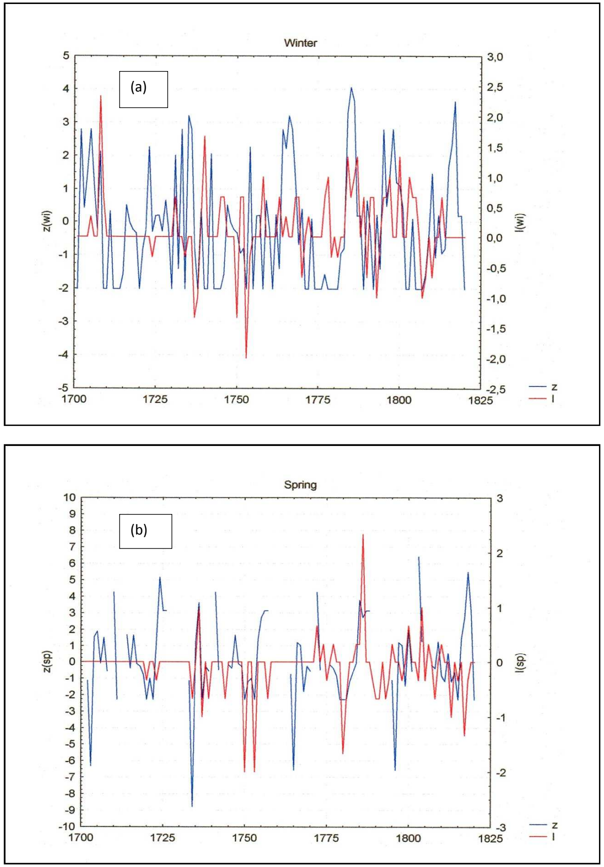

Fig. 9. Comparison between reconstructed regional standardized anomalies (z) and rogations index of Seville (I) for winter **(a)**, and spring **(b)**, during the period 1701–1820.

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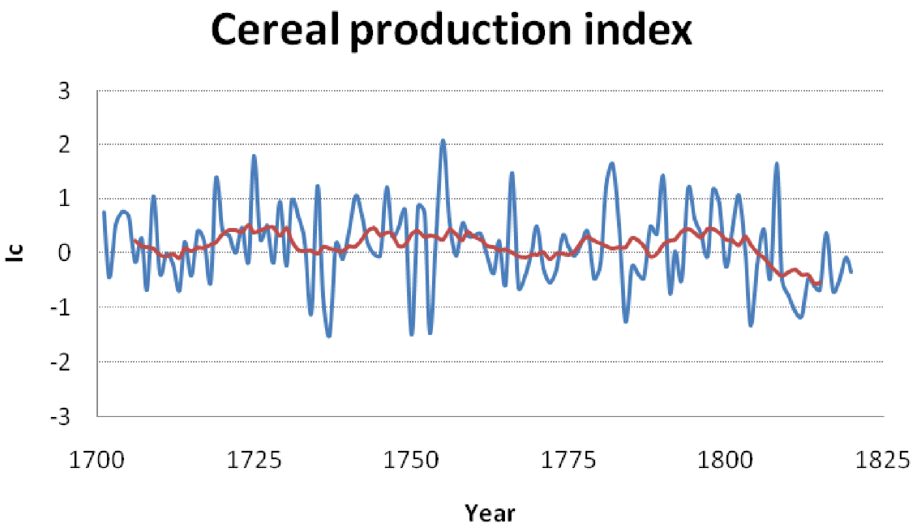

Fig. 10. Index of cereal production for the Guadalquivir River Basin, period 1701–1820. Red line: 11-yr moving average.

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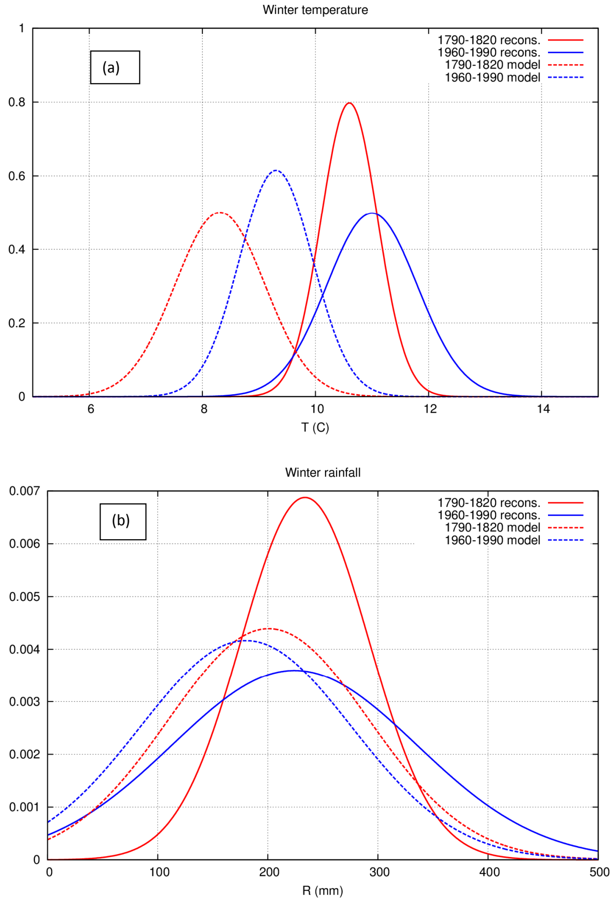

Fig. 11. Density functions of the periods 1790–1820 (red) and 1960–1990 (blue) for winter temperature **(a)** and rainfall **(b)**. Dashed lines correspond to model simulations.

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