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# The climate in Zafra from 1750 to 1840: precipitation

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**Abstract** In this work, we present the construction of a rainfall index for Zafra (southwestern Spain) during the period 1750–1840 from documentary sources. For this purpose we used the correspondence of the Duke of Feria that contains a quasi-weekly report of the weather in Zafra. In order to check its reliability, the Zafra rainfall index was compared with the short rainfall series available from relatively close stations, including Lisbon, Mafra, Seville and Gibraltar, all of which show a similar pattern. We also studied the atmospheric circulation over North Atlantic and western Europe in the period 1750–1840 for the months characterized by extreme values of the percentage of rainy weeks in the period 1750–1840, specifically those months above the 95th percentile or below the 5th percentile. The average large-scale atmospheric circulation maps corresponding to the months with high percentages of rainy weeks have negative Sea Level Pressure (SLP) anomalies around southwestern Iberian Peninsula (IP) and higher than usual SLP around Iceland. On the other hand, the maps corresponding to the winter months with low percentages of rainy weeks are dominated by an anticyclonic circulation over the south Europe affecting southwestern IP. The monthly rainfall index anomalies for the study period were calculated and results show two wet period (from 1782 to 1789 and from 1799 to 1807) and two dry ones (from 1796 to 1799 and from 1816 to 1819) in accordance with other regional precipitation series available.

## 1 Introduction

The use of indices in historical climatology started in the 1970s (Lamb 1977). This method consists on establishing a graded scaling system to transform documentary evidence in an ordinal number system. Different scales of indices for series of temperature and precipitation

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**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-014-1315-9) contains supplementary material, which is available to authorized users.

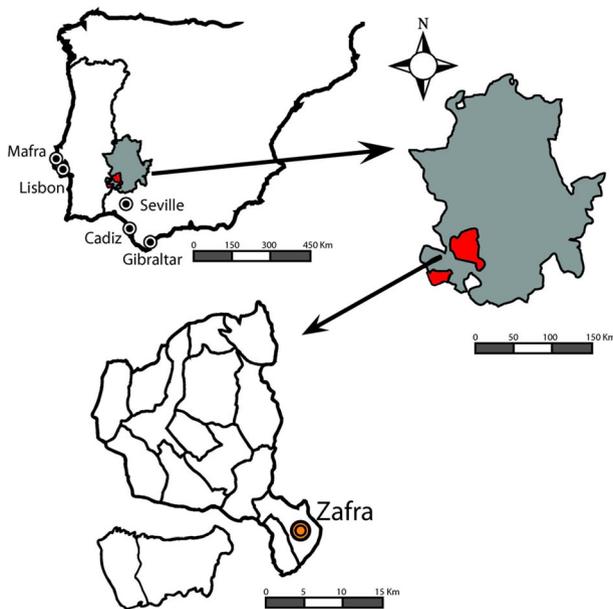
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have been used (Pfister 1984; Rodrigo et al. 1994; Diodato 2007; Kelso and Vogel 2007; Camuffo et al. 2010; Dobrovolný et al. 2010).

The construction of long-term series of indices is often a painstaking process as it requires a widespread study and knowledge of the historical sources. In the process of transforming the documentary evidence into a simple numeric scale, it is essential to minimize subjectivity (Brázdil et al. 2010a). Until now the majority of the works undertaken on historical climate topics correspond essentially to information associated to extreme events (droughts, storms, floods, snowfalls...), as a consequence of the biased tendency to report only unusual weather/climate phenomena (Brázdil 1996; Barriendos and Martín-Vide 1998; Alcoforado et al. 2000; Vaquero et al. 2008; Glaser et al. 2010; Grab and Nash 2010; Domínguez-Castro et al. 2012a, 2013; Zheng et al. 2012; Enzi et al. 2013). The criterion adopted in this type of sources usually consists on designing a seasonal ordinal index integrated into the estimation of extremes to characterize the rainfall. Here, the source used in this paper is of a slightly different nature, consisting of weekly weather descriptions associated to the town/region of Zafra, capital of Duchy of Feria in the southwest of Spain (Fig. 1). These reports are conserved in the section “*Consultas y Decretos del Ducado de Feria*” of the Municipal Archive of Zafra. The Duke lived in Madrid but he was informed on a regular basis (virtually every week) about events taking place in his Duchy. The knowledge of the weather was relevant for the Duke due to the impact of meteorological parameters in crops (both in terms of crop yield and timing of the harvest) and therefore influencing the price of cereals (for more details see Fernández-Fernández et al. 2014). Thus, the main purpose of this work is to present the first high-resolution construction of rainfall index in the southwestern Spain, derived from weekly weather descriptions.



**Fig. 1** Location map over the Iberian Peninsula. Red area is the Duchy of Feria and grey area is the region of Extremadura

## 2 Construction of precipitation indices

The quasi-weekly weather descriptions in the “*Consultas y Decretos del Ducado de FERIA*” were carefully analyzed (Fernández-Fernández et al. 2014) to look for the best index possible. The “*Consultas*” provides information about the presence or absence of rainfall, the intensity and approximate number of rainy days during the previous period under consideration (typically 1 week). However, the information about the intensity or number of rainy days is not continuous at the daily scale, hampering the possibility of devising a continuous rainy time series. Some typical examples of the reports contents are shown below:

*April, 18th 1785* “Continúa el tiempo muy benigno a los campos cayendo algunas lluvias muy ligeras que es lo que necesitan”. [“The weather continues very nice for the field falling some rains very light as it needs.”]

*December, 30th 1833* “El tiempo continúa seco sin haver llovido más que lo muy preciso para hacer las sementeras que no tardarán en resentirse de la falta de agua”. [“The weather continues dry, only rained enough for doing sown filed which will suffer soon the lack of water.”]

We must emphasize that the only objective information about rainfall provided continuously in the documentation is its presence or absence at the quasi-weekly temporal scale. Thus, we established two categories for our rainfall index: value 0 (value 1) indicates total absence (at least 1 day) of precipitation during the days reported. The index value was assigned to each individual day of one report. Based on this definition, a quasi-weekly series was constructed to inform if it rained or not during that week. In order to facilitate we will refer to the time scale adopted as being “weekly”, despite acknowledging that some reports were relative to shorter periods (e.g., 3 or 4 days). The percentage of weeks in the month with index 0 and index 1 was calculated considering the need to split some weeks by two continuous months. We have deleted from our data series those monthly values with less than 50 % of days covered by the documents, i.e., if we have only 2 week reports within a month, that month is excluded from the rest of analysis. Overall this restriction applies to 64 months in total (out of 892 months). A deeper description and discussion of the indexing methodology is available as supplementary electronic material.

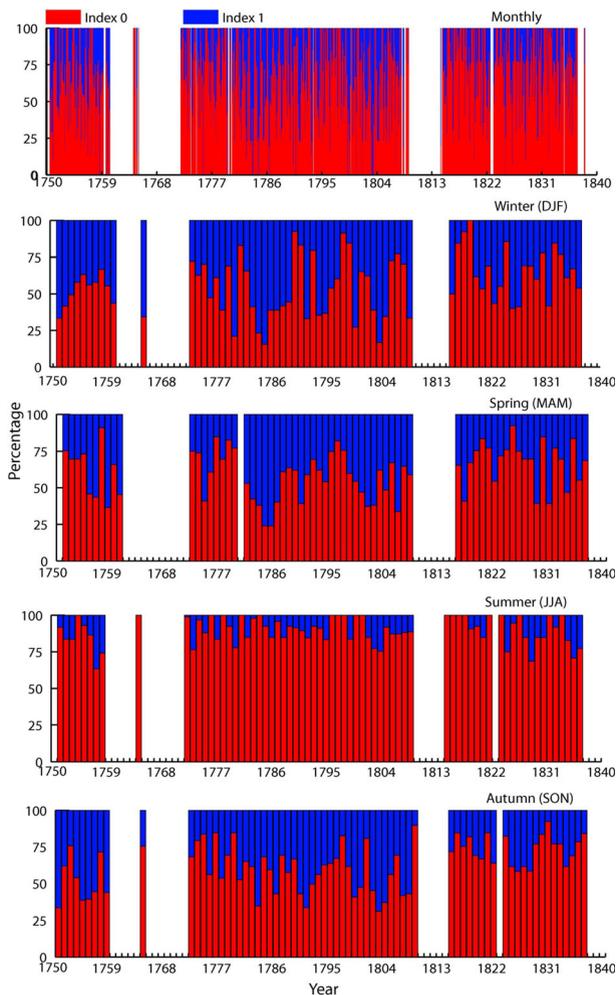
The Cumulative Deviations test was used to check the homogeneity of the monthly percentage of rainy weeks for the period 1750–1840. This test is based on the adjusted partial sums or cumulative deviations from the mean (Buishand 1982). The results showed that there is a changepoint in the series in 1809. This changepoint could be due to the gaps in the series between 1810 and 1816. A correlation analysis was performed between the percentage of rainy weeks and cumulated precipitation in each season in Zafra for the period 1960–1990. The results show high Pearson correlation coefficients between both variables in winter (0.638  $p$ -value=0.00015) and autumn (0.812,  $p$ -value<0.0001). For spring and summer the Pearson correlation coefficients were 0.634 ( $p$ -value=0.00013) and 0.488 ( $p$ -value=0.0072) respectively.

Figure 2 shows the monthly and seasonal percentages of dry weeks (index 0) and rainy weeks (index 1) from 1750 to 1840 in Zafra. In general, a large inter-annual variability of rainfall can be observed in all the series. In particular, it is immediately striking that during the period 1770–1810 higher percentages of rainy weeks were observed than in the last decades of the study period. The wettest sub-periods correspond to the early years of 1780s and of 1800s. If we assess on a seasonal basis, the years that

reached the highest percentages of rainy weeks in winter were 1780, 1784, 1785, 1792, 1800 and 1804 (higher than 70 % of rainy weeks). In spring, the years that presented percentages of rainy weeks higher than 70 % were 1784 and 1785. As expected in summer, in southern Iberia, there were not years with percentages of rainy weeks higher than 40 %. Finally, in autumn, the period 1815–1840 showed lower percentages of rainy weeks than the period 1750–1810.

### 3 Reliability of the index

In order to check the reliability of the rainfall index, in the following subsections we studied the relationship of our index series with instrumental data available for short periods. We also

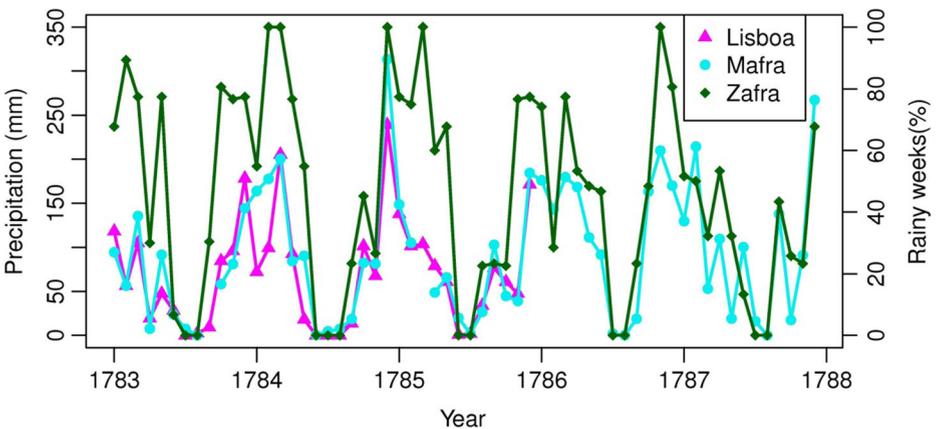


**Fig. 2** Percentages of dry weeks (red bars) and rainy weeks (blue bars) from 1750 to 1840 in Zafrá

analyzed the atmospheric circulation over the North Atlantic and Europe during the wet and dry winter months of the considered period.

### 3.1 Comparison with instrumental data

We compared the percentage of rainy weeks in the rainfall index series of Zafrá with early available meteorological measurement in Lisbon and Mafra (Alcoforado et al. 2012) (see Fig. 3). It should be stressed that this southwestern sector of Iberia is characterized by similar temporal intra-annual and inter-annual variability at the month and seasonal scales. This relatively synchronous behavior between stations such as Lisbon, Seville, Badajoz or Zafrá (Fig. 1) results from the similar precipitation regime driven by the same large-scale atmospheric circulation patterns, namely the North Atlantic Oscillation (NAO), the East-Atlantic and the Scandinavian pattern (Trigo et al. 2008). Nevertheless, the most prominent pattern corresponds to the NAO (Zorita et al. 1992) that explains about 50 % of the variance (Rodó et al. 1997; Trigo et al. 2004). This strong impact of NAO is directly associate to the control exerted by NAO on the location of the storm-tracks affecting western Iberia (Trigo et al. 2002) thus imposing similar patterns of precipitation (Serrano et al. 1999). Lisbon has instrumental monthly rainfall available from 1783 to 1785, 1789 and 1793 and Mafra from 1783 to 1787. The common period to all series was 1783–1785. Results showed that December of 1784 was the wettest month of Mafra and Lisbon rainfall series and rainfall index series in Zafrá presented a percentage of rainy weeks (i.e., 100 %). March 1784 was also a very rainy month in all series. The correlation coefficient estimated between Zafrá and Mafra series and between Zafrá and Lisbon series was 0.73 ( $p$ -value<0.0001) and 0.78 ( $p$ -value<0.0001), respectively. We also compared the rainfall in Zafrá and Lisbon in the current period (1960–1990). To achieve this, we constructed a similar rainfall index relative to the current period for series Lisbon and Zafrá (Index 0: indicates absence of rainfall during the days relating to 1 week without rainfall. Index: 1 indicates presence of rainfall during the days relating to 1 week with rainfall). The correlation coefficient estimated is 0.755 ( $p$ -value<0.0001).

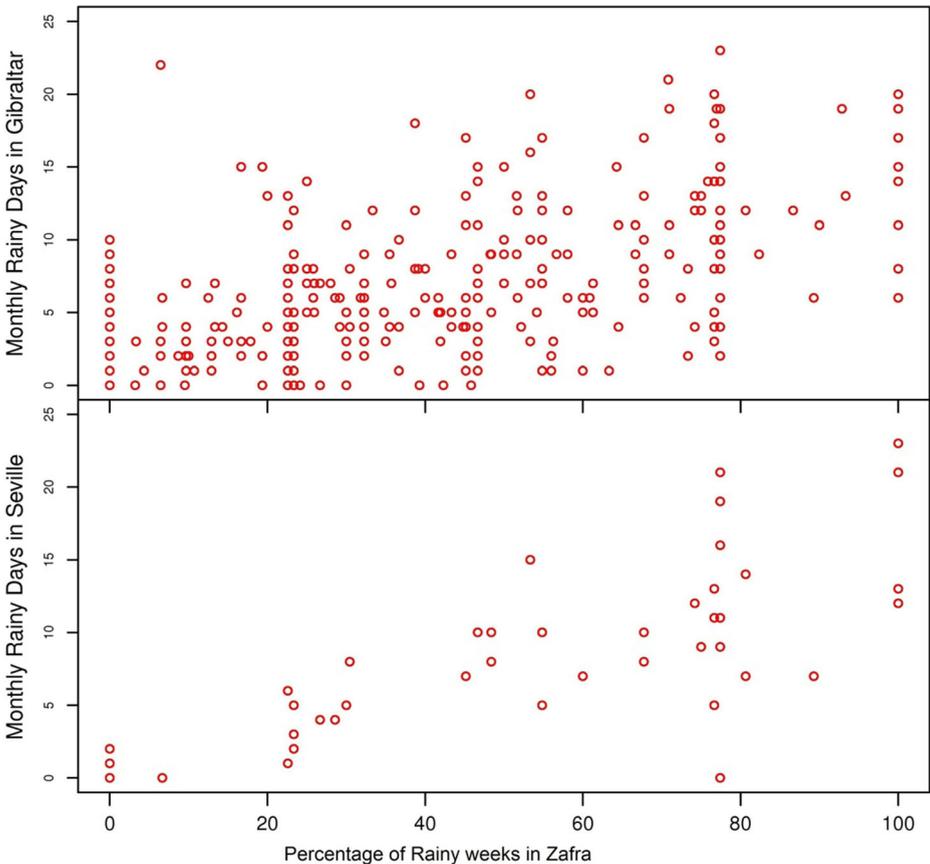


**Fig. 3** Monthly rainfall total in Lisbon and Mafra and monthly percentage of rainy weeks in Zafrá for the period 1783–1787

On the other hand, we compared the percentage of rainy weeks (i.e., values equal to one in the rainfall index series in Zafra) with monthly number of rainy days in Gibraltar, where such information is readily available (Wheeler 2007; 2012) for the periods 1777–1795, 1804–1810 and 1821–1832 (see Fig. 4a). Additionally, we also provide a similar comparison with the number of rainy days in Seville (Dominguez-Castro et al. 2014) for 1783–1786 (Fig. 4b). Overall, it is possible to confirm that high percentages of rainy weeks presented high number of rainy day in Gibraltar and Seville. The Pearson correlation coefficient between the percentage of rainy weeks and the number of rainy days in Gibraltar for the period 1777–1795, 1804–1810 and 1821–1832 was 0.65 ( $p$ -value<0.0001). For the case of Seville, the Pearson correlation coefficient estimated was 0.79 ( $p$ -value<0.0001).

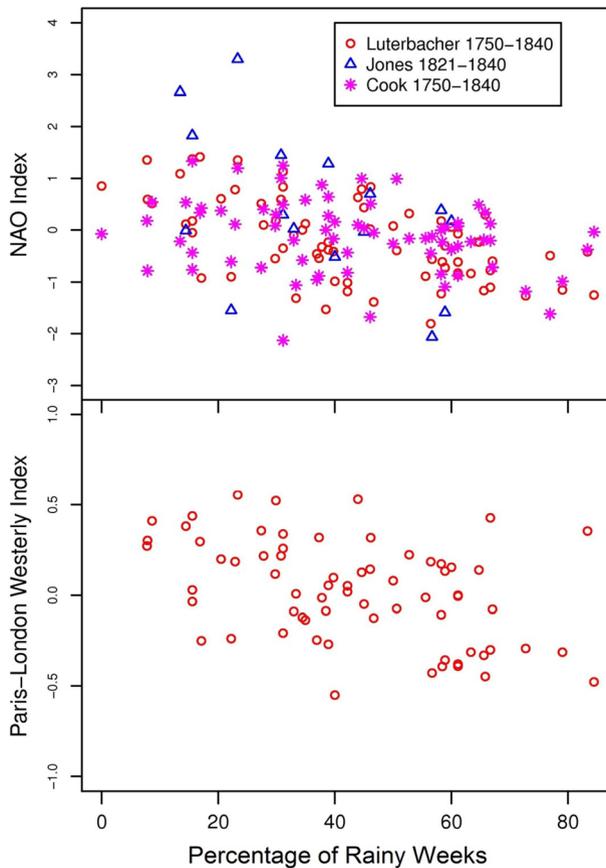
### 3.2 Relationship between the rainfall in Zafra and NAO and Paris-London westerly indices

The NAO is one of the most prominent and recurrent patterns of atmospheric circulation variability over the middle and high latitudes of the Northern Hemisphere especially



**Fig. 4** Relationships between the percentage of rainy weeks in Zafra and number of rainy days in Gibraltar (a) for the periods 1777–1795, 1804–1810 and 1821–1832 and Seville (b) for the period 1783–1786

during the winter months (Hurrell et al. 2003). Several works have demonstrated the profound influence of the NAO on winter rainfall over the Iberian Peninsula (IP) (e.g., Trigo et al. 2004; Gallego et al. 2005). Typically, negative values of the NAO index are related to intense rains in winter over the southwest and interior of the IP (Rodó et al. 1997; Trigo et al. 2004; Gallego et al. 2005). Here, we studied the relationship between the seasonal average of rainfall for the winter in Zafra and the winter NAO index using two widely used reconstructions (Luterbacher et al. 2002a; Cook et al. 2002), as well as the longest instrumental index available (Jones et al. 1997). Fig. 5a shows the relationship between the various seasonal NAO indexes and the seasonal percentage of rainy weeks of the Zafra rainfall index in winter. Blue triangles correspond to the instrumental NAO values compiled by Jones et al. (1997) for the period 1821–1840. Red circles and pink asterisks indicate the relationship between the Zafra winter series and the NAO index reconstructions of Luterbacher et al. (2002a) and Cook et al. (2002), respectively, both from 1750 to 1840. In general, our Zafra rainfall index series presents a clear link with all NAO indices series used. More specifically, one can observe that the wettest winters correspond to predominantly negative values of reconstructed NAO. For the



**Fig. 5** Relationship between the winter percentages of rainy weeks and different long-term time series of the NAO index (a) and Paris-London westerly index (b) in the period 1750–1840

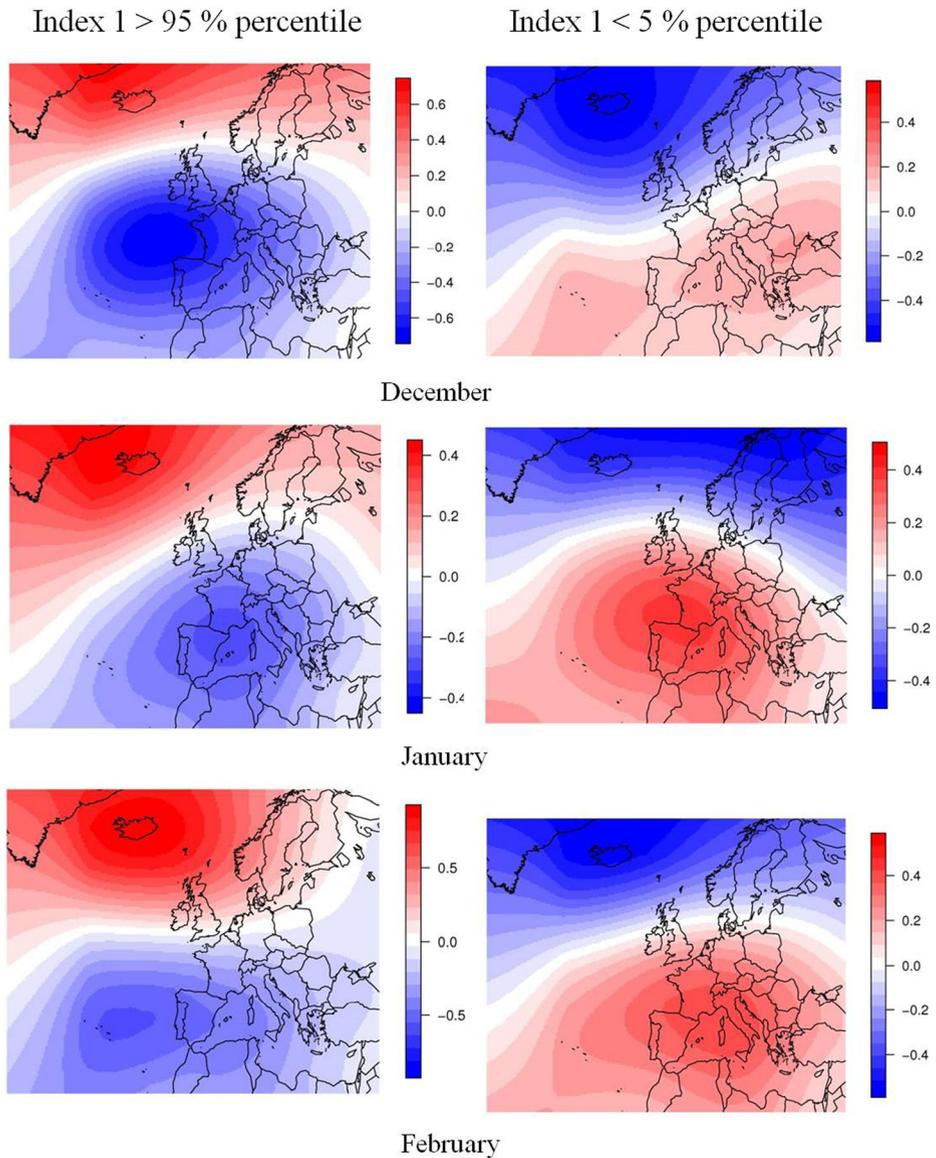
years characterized by a high percentage of rainy weeks in Zafra (>50 %), the reconstructed NAO index presents a negative value in more than 80 and 75 % of the years, for the reconstructions of Luterbacher et al. (2002a) and Cook et al. (2002) respectively. However, the highest (lowest) percentages of rainy weeks show values more negative (positive) of instrumental NAO index than those relative to NAO reconstructions. The Pearson correlation coefficient between the percentage of rainy weeks and NAO index reconstruction of Luterbacher et al. (2002a) and Cook et al. (2002) was  $-0.57$  ( $p$ -value  $< 0.001$ ) and  $-0.27$  ( $p$ -value =  $0.0257$ ) respectively. The correlation coefficient between the percentage of rainy weeks and NAO index instrumental series by Jones et al. (1997) was  $-0.52$  ( $p$ -value =  $0.0380$ ). We also studied the relationship between the winter percentage of rainy weeks in Zafra and the corresponding winter NAO index during the period 1960–1990 showing a correlation coefficient of  $-0.65$  ( $p$ -value =  $0.0001$ ).

Additionally, we studied the relationship of the Paris-London westerly index with the winter rainfall in Zafra. Slonosky et al. (2000) demonstrated that an index constructed from the difference in mean sea level pressure between London and Paris can provide a measure of westerly flow across Western Europe, which is closely related with the traditional NAO indices especially during the winter months (Barriopedro et al. 2014). Slonosky et al. (2000) extended back to 1774 the Paris-London index and the relationship between the Paris-London index (1774–2000) and several NAO indices were examined by Jones et al. (2003). Recently, the Paris-London index was extended further back until 1692 by Cornes et al. (2012). The relationship between the percentage of rainy weeks in winter and the winter Paris-London index for the period 1750–1840 is plotted in Fig. 5b. Results indicate that when the percentage of rainy weeks increases, the Paris-London index value decreased. Specifically, high percentages of rainy weeks are related to predominately negative values of the Paris-London index. The Pearson correlation coefficient between the percentage of rainy weeks and the winter Paris-London index is  $-0.44$  ( $p$ -value =  $0.0001$ ).

### 3.3 Anomalies of sea level pressure over the Eastern North Atlantic and Europe during the extreme rainfall indices periods

Precipitation variations are closely linked to the atmospheric circulation (Hurrell et al. 2003). Therefore, we decided to perform a study of the Sea Level Pressure (SLP) fields for the wettest season (winter) with extreme percentage of monthly rainfall index in the period 1750–1840.

We used the SLP database developed by Luterbacher et al. (2002b) as this covers the entire period considered here. In order to check for possible extreme weather situations, the analysis of SLP relative anomalies were performed for the months characterized by extreme values of the percentage of Zafra rainfall index 1 in the period 1750–1840, specifically those months above the 95th percentile or below the 5th percentile. Figure 6 shows the SLP relative average anomalies for those winter months: left panels present the months which had percentage of index 1 above 95th percentile while right panels show the equivalent for months below 5th percentile (notice the different scale employed). In winter months with percentage of rainfall weeks above 95th percentile, we observe negative SLP anomalies around southwestern Europe with enhanced anticyclonic circulation over the eastern Atlantic at high latitudes, close to Iceland. This synoptic situation is associated to the highest rainfall over Iberian Peninsula (Zorita et al. 1992), resembling the impact over high resolution IP precipitation associated with



**Fig. 6** Maps of average anomalies (%) of Sea Level Pressure for the winter months (December, January and February) for the period 1750–1840: *left (right)* column shows the maps for the months with percentage of index 1 above (*below*) the 95th (5th) percentile. Note that each map has its own scale

the W and SW weather types (Cortesi et al. 2013) and compatible with a negative NAO configuration (Trigo et al. 2004). The winter months with percentage of rainy weeks below the 5th percentile present higher than normal sea level pressure over southwestern Europe whilst negative anomalies are displaced to high latitudes resembling the positive phase of NAO pattern (Trigo et al. 2004; Gallego et al. 2005).

#### 4 Rainfall anomalies in Zafra

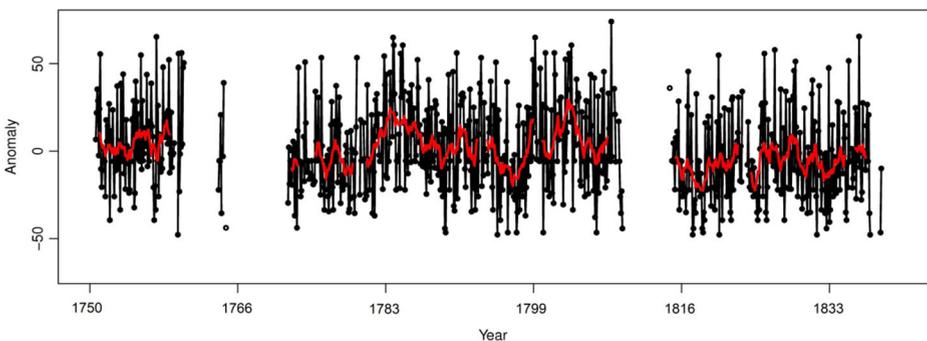
To analyze and detect dry and wet periods in Zafra from 1750 to 1840 we have calculated monthly rainfall index anomalies for our study period. The monthly rainfall index anomalies were estimated using the period 1750–1840. Specifically, the anomalies were computed as follow:

$$PA_{ji} = P_{ji} - \bar{P}_i$$

where  $PA_{ji}$  refers to monthly rainfall anomalies in the month  $i$  of the year  $j$ ,  $P_{ji}$  is the percentage of rainy weeks in the month  $i$  of the year  $j$  and  $\bar{P}_i$  the average percentage of rainy weeks in the month  $i$  for the period 1750–1840.

Figure 7 shows the monthly rainfall index anomalies in Zafra for the period 1750–1840. The red line represents a 12-month moving average. A number of wet and dry sub-periods should be emphasized:

**1782–1789** This period corresponds to a prolonged wet period. Winter months that reached values of 100 % of rainy weeks were observed in February and December 1784. Likewise, February of 1783 and December 1786 reached rainy week percentages of 89.3 and 81 %, respectively. In relation to particularly wet autumn months, November 1786 presented rainfall in every week of the month, while October 1783 reached values of 81 % of rainy weeks. Finally for spring months, March 1783 and 1785 present rainfall in every week. Similar behaviors were detected in other Mediterranean regions between 1784 and 1789 (Font-Tullot 1988; Barriendos and Llasat 2003) and Central Europe (Kington 1988; Brázdil et al. 2010b). In relation to southern Iberia, all the above mentioned months were characterized by high numbers of monthly rainy days in Gibraltar and Seville for the period 1783–1786 (Domínguez-Castro et al. 2014). Instrumental data from Lisbon and Mafra confirmed the existence of a wet period in Portugal between 1784 and 1789 (Alcoforado et al. 2012). According to D'Arrigo et al. (2011), the intense rains could be due to negative North Atlantic Oscillation in combination with El Niño-Southern Oscillation warm event. In addition, the large eruptions of Lakigar in 1783/1784 (Thodarson and Self 2003) could affect to the occurrence of this wet period (1782–1789).



**Fig. 7** Rainfall monthly anomalies for the period 1750–1840. The red line represents a 12-month moving average

*1796–1799* This corresponds to a dry period, where the years that registered the lowest percentage of rainy weeks in winter were 1798 and 1799. In particular, during the months of January 1797, January 1798, February 1798 and November 1799 rainfall was not observed at all. During February 1796 the percentage of Zafra dry weeks (rainfall index 0) was 97 %. The effect of this prolonged dry episode in IP can be supported by the record of rogation ceremonies, mainly during the winter and spring of 1798. During these seasons several locations from south (Seville), center (Toledo, Teruel) north (Calahorra, Zaragoza) and Mediterranean area (Murcia, Girona, Cervera, Tarragona, Tortosa, Vic) celebrated *pro-pluvia* rogation ceremonies (Dominguez-Castro et al. 2012b).

*1801–1807* This period corresponds to the second wet period with several winter and autumn seasons reaching the highest values of rainy weeks in Zafra. November 1803, December 1803 and January 1804 presented rainfall in every week. This winter of 1803/1804 was particularly rainy, as it is confirmed by the occurrence of floods in several rivers in Andalucía, namely the rivers Guadalquivir (Seville), Guadaira (Seville) and Darro (Granada) (CNPC-CTI 1983–1985).

*1816–1819* This corresponds to the second dry period with the years 1817 and 1818 presenting the lowest percentages of rainfall weeks. Some of the driest months were observed during the winter season. In particular, February and December 1817, December 1818 and January and February 1819 did not registered any rainy week. Finally, in autumn, all months showed high values of percentage of dry weeks. This dry period has been also found in other sectors of Iberia as shown by Trigo et al. (2009), with an extended version by Domínguez-Castro et al. (2012b). These later authors identified the 1817 as the year with the most extended drought in Iberia for the period 1750–1850, according with the number of *pro pluvia* rogations celebrated.

## 5 Conclusions

The lack of meteorological networks prior to the mid-nineteenth century in the southwestern IP feeds the development and use of proxies (natural and documentary) to improve our knowledge of the climate of the past centuries. In this paper, we have presented the first high-resolution long-term rainfall index for the southwest of the IP during the period 1750–1840 using documentary sources. The documentary source used has an unusually high temporal resolution providing weekly weather description during the whole period (Fernández-Fernández et al. 2014).

In order to evaluate the rainfall index reliability it was compared with the existing short overlapping instrumental series in the southwest IP (Mafra, Lisbon, Seville and Gibraltar). Generally all these observed precipitation time series show a similar temporal evolution pattern and high correlations with the index.

It is a well-known fact that the winter precipitation in the southwest of IP is largely influenced by NAO. So we have studied the relationship between the Zafra rainfall index and different NAO indices. Results showed that the extreme values of rainfall in Zafra are better connected with the instrumental NAO index than with the reconstructed NAO indices.

From a wider atmospheric circulation perspective, we have studied the Sea Level Pressure (SLP) fields for the winter months with percentage of rainy weeks above (below) the 95th (5th) percentile during the study period. Results showed that the synoptic situations observed are according to the expected for the southwest of IP (negative SLP anomalies around southwestern Europe for rainy winters and positive SLP anomaly over southwestern Europe for dry winters).

The monthly rainfall index anomalies for the study period show two wet periods (from 1782 to 1789 and 1800 to 1807) and two dry periods (from 1796 to 1799 and 1816 to 1819). The studied period was affected by some large external forcing factors including the Dalton minimum of solar activity ([Wagner and Zorita 2005](#); [Vaquero 2007](#)), but also several large eruptions such as Lakigar ([Thodarson and Self 2003](#)) and Tambora ([Stothers 1984](#)). These external forcing most likely played an important role affecting to the climate variability observed during the period 1750–1840 ([Wagner and Zorita 2005](#)).

In this work we have focused on the only rain related variable that we could derive from the frequent reports sent to the Duchy of Zafra. However, these reports also include information related to temperature (variability and extremes) as this was equally important to understand the inter-annual variability of cereals crop production ([Fernández-Fernández et al. 2014](#)) and may be worth of further investigation.

Finally we are confident that this study, based on a non-standard source of meteorological proxy information, will prompt other groups to look for similar sources in analogous contexts, namely archives with long records of correspondence of large landowners of southern Europe (i.e., Spain, Italy or Portugal).

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