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Reconstruction and homogenization of the longest instrumental precipitation series in the Iberian Peninsula (Barcelona, 1786–2014)

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ABSTRACT: Detection and reconstruction of early instrumental series is an interdisciplinary activity that allows us to extend climate data records to periods prior to the mid-19th century, extending the overlapping periods with climate proxies and characterizing extreme events. In this work, the collection of several data sources corresponding to different periods and locations, obtained with a wide range of methods and instruments by institutions or private observers, provides the following results: Barcelona has a continuous rainfall series with monthly resolution since 1786 and with daily resolution since 1850. It is worth mentioning that the records from Barcelona provide the longest continuous monthly series available on rainfall in the Iberian Peninsula. The monthly records have been homogenized by using a relative homogenization approach, HOMER. The results highlight the existence of five breaks, most of them due to relocations or instrumentation changes documented in the metadata, which have been adjusted to remove non-climatic factors. The homogenized annual and winter precipitation series in Barcelona show a statistically significant increase from 1786 to 2014, although this increase is mainly due to the concentration of negative anomalies during the first half of the 19th century, which is also clearly visible in the seasonal series. Specifically, an extreme mega-drought episode was observed from the 1810s to the 1830s, which is supported by different proxy data. For a better dissemination of the homogenized monthly series developed in this study, the data set is freely available to the research community.

KEY WORDS data rescue; rainfall time series; homogeneity; early instrumental period; long-term variability; Barcelona; Iberian Peninsula

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1. Introduction

Detection, recovery and evaluation of old instrumental series involve complex research because it requires an interdisciplinary effort. Historiographic research and recovery work is required to bring the information into to the current meteorological data formats. This research is justified to a great extent by the uncertainty due to the observation of human-induced climate change (Hartmann *et al.*, 2013; Stocker *et al.*, 2013). Rainfall is especially relevant, because its variability and trends over time coincides directly with the production and management of water resources (e.g. Dai *et al.*, 2009). On a global scale, there is detectable evidence of anthropogenic forcing on observed precipitation in different latitudinal bands (Zhang *et al.*, 2007; Min *et al.*, 2011). Nonetheless, on more reduced scales, there still exists great uncertainty (Hegerl and Zwiers, 2011), with the Mediterranean region being one of the most prone areas to be affected by global warming (Gao and Giorgi, 2008; Barkhordarian *et al.*, 2013; Gonçalves *et al.*, 2014).

In recent decades, several research projects and initiatives have allowed the recovery of old instrumental climate records, especially in northern and central Europe (among others, ADVICE, IMPROVE, EMULATE, ALP-IMP and MILLENNIUM). Most of the initiatives have focused on temperature and air pressure data rescue and homogenization for large geographic areas (Böhm *et al.*, 2001; Slonosky *et al.*, 2001), while more scarce have been those who have tried other variables such as rainfall (Auer *et al.*, 2005). At the same time, and depending on the difficulty and research effort required, instrumental series for specific locations have been recovered and published, including sites such as Edinburgh (Jones and Lister, 2004) or Armagh (Butler *et al.*, 2005).

In the Mediterranean context, meteorological data rescue initiatives have been less successful, despite the wide availability of information in the archives (Barriendos *et al.*, 2002; Camuffo, 2002; Cocheo and Camuffo, 2002; Maugeri *et al.*, 2002a, 2002b; Camuffo *et al.*, 2010; Brunet *et al.*, 2013). Especially for precipitation series,

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recovery and homogenization projects are even less numerous despite being a variable of great interest for its great spatial and temporal variability (Camuffo *et al.*, 2013).

Regarding the Iberian Peninsula, there are many studies of rainfall trend analysis during the instrumental period, especially with data generated by the Spanish and Portuguese meteorological services since late 19th century (e.g. Almarza *et al.*, 1996; Saladié *et al.*, 2007; González-Hidalgo *et al.*, 2011; de Lima *et al.*, 2015). The high rainfall variability in this area is a matter of detailed analysis, as precipitation is the basis of water resources and the main origin of frequent and serious climate extreme events (Wheeler and Martin-Vide, 1992; Esteban-Parra *et al.*, 1998; Lana and Burgueño, 2000; Martin-Vide, 2004; Gallego *et al.*, 2011). In the case of the city of Barcelona, rainfall data have been compiled and analysed but only in its modern period, from the mid-19th century when official institutions were created (Rodríguez *et al.*, 1999; Lana *et al.*, 2003). The known meteorological series for the early instrumental period (EIP) are not very rich in the Iberian Peninsula and availability is not optimal (Dominguez-Castro *et al.*, 2014). Nevertheless, the recovery and analysis of some complete series has been possible such as those from Gibraltar (Wheeler, 2006), the temperature and air pressure in Cadiz (Barriendos *et al.*, 2002) and the atmospheric pressure in Barcelona (Rodríguez *et al.*, 2001).

This article presents the recovery of the monthly (from 1786) and daily (from 1850) rainfall observations in Barcelona (Catalonia, Spain). On this continuous series, which at the moment can be considered as the longest and oldest that exists for Iberia, some previous partial and specific papers have been written (Barriendos, 2008a, 2008b; Barriendos *et al.*, 2010; Camuffo *et al.*, 2013; Dominguez-Castro *et al.*, 2014). Nevertheless, an exhaustive study of all the existing rainfall data, assembling the different series available in the city, was still lacking as well as a deeper evaluation of the temporal homogeneity. At this step, the activities required for this have been possible; thanks to the scientific and economic support of the *Servei Meteorològic de Catalunya* (SMC, Meteorological Service of Catalonia).

This article first describes the historical context and the documental sources that preserve the records and their digitization process (Sections 2 and 3). Next, the quality and homogeneity of the joint series of Barcelona is evaluated and a homogeneous, continuous and complete monthly series from 1786 to the present is proposed (Section 4). Finally, the main characteristics of the temporal variability of precipitation in Barcelona and their trends are presented (Section 5).

2. History of meteorological observations in Barcelona: a tale of relocations

A description of the main features of meteorological observation is necessary when dealing with series of data covering a time period of more than two centuries. There is no doubt that a series of positive and negative factors, representing different social contexts, converge in the final result of this series. Important changes have also occurred in the very concept of meteorological observations, and in the instrumentation, the observational procedures and in the data storage. The main stages of the meteorological observations in Barcelona (i.e. observers, institutions involved and initiatives) are shown through this section, while details on the available metadata (i.e. sources of data and location) are provided in Section 3.

2.1. Initial period: 1780–1853

The start of instrumental meteorological observations in Barcelona was due to an initiative of the medical profession. The city had experienced strong demographic growth during the 18th century, accompanied by an incipient and successful industrialization, similar to that which other European regions were experiencing. As a result, living conditions in urban environments were deteriorating rapidly, with new phenomena appearing against which the authorities could do little (industrial waste, environmental pollution and deterioration of water supplies). In consequence, doctors were the most sensitive to this new environmental conditions and their relationship with public health conditions, and led them to organize academies, following the dynamics of the era in many other scientific areas.

In 1770 the *Academia Médico-Práctica de Barcelona*, now known as the *Reial Acadèmia de Medicina de Catalunya* (Royal Academy of Medicine of Catalonia), was established. At the same time, in connection with the monitoring of atmospheric conditions, several events took place during the second half of the 18th century that contributed to the inception of meteorological observation in Barcelona. Of particular importance, were the publication of a treatise on meteorology that provided guidelines for its instrumental observation (Cotte, 1774), and the establishment in 1776 of the *Société Royale de Medicine de Paris*, with meteorological observation and public dissemination of the data constituting an important part of its activities. Within this context, in October 1779, the *Academia Médico-Práctica de Barcelona* suggested to start a similar initiative in the city (Bonells, 1798).

The tasks of meteorological observation in Barcelona fell on Dr. Francesc Salvà (1751–1828), who had recently received his doctorate in medicine at the University of Toulouse (France). Observations began in January 1780 in the doctor’s home, in the city centre of Barcelona (11, Petritxol street) and continued without interruption for 47 years, until 1 year before his death. Dr. Salvà took care to teach some medical colleagues, and this allowed the observations to continue. The observer who is known for continuing the series in 1827 up to 1854 was doctor Pere Vieta (1779–1856), who rose the post of Vice Rector of the University of Barcelona.

2.2. Transition period: 1854–1936

The central decades of the 19th century saw the coexistence of meteorological observers from the area of medicine and the implementation of the first official observatory, which was driven by the Spanish Government and managed by personnel of the University of Barcelona.

The doctors continued with the observations because environmental and public health conditions in Barcelona had worsened with respect to the mid-18th century. When Dr. Vieta could no longer continue his work, Dr. Joan Ramon Campaner (1812–1876) replaced him. He purchased new instruments in London and installed them at a new site in the building of the *Reial Acadèmia de Medicina*. His work endured from 1854 to 1876 (Escudé and Corbella, 2003) and the data were used in different studies that the academic authorities of Barcelona conducted to address the public health problems existing. The *Reial Acadèmia de Medicina* published the data in their periodic publications, and in addition were sent daily to the local press for the benefit of the general public. Albert Burkhart, an optician with an establishment in the centre of Barcelona, continued Campaner's meteorological records with renewed instruments from 1876 to 1885. He was the last doctor, along with Dr. Joan Montserrat, who carried out meteorological observations in the city and they were being also published daily in the local press. Therefore, in 1885, the active role of the physicians as meteorological observers ceased.

In the mid-19th century, the Spanish government, following the trend of other countries promoted the creation of a network of meteorological stations with the aim of centralizing continuous information on weather evolution. The initiative had a modest start, using the university structure: the science faculties received the assignment of putting into operation meteorological observatories and sending the data to a central service (Royal Order, March 30, 1846). In 1850, the General Directorate of Public Instruction established 23 meteorological stations. A Royal Decree dated the 3rd of November 1856 created the General Statistics Commission of the United Kingdom, the first organization that had the specific assignment of coordinating meteorological observation and preserving and publishing the resulting data (García and Giménez, 1985).

In Barcelona, official meteorological observation began on the 1st of January 1855, in a provisional building (the former *Convent del Carme*), with very precarious conditions that were compensated by the training and dedication of the academic personnel. Once the new building of the University of Barcelona was constructed, the instruments were transferred and the personnel were able to resume their activity on the 1st of April 1882. This official activity was maintained with complete regularity until the beginning of the Civil War: the last observation was recorded on the 9th of August 1936.

Coinciding with the official records, during this period there were other private initiatives that deserve to be mentioned in the field of meteorological observations. Such is the case of Dr. Llorenç Presas, a science professor at the University of Barcelona, who installed an excellent observatory in his home, in operation between 1849 and 1874. And also the observations made by another doctor, Joan Montserrat for a shorter period (1881–1885). Both initiatives may cover overlapping periods between observatories.

2.3. Period of dispersion and the role of the Fabra Observatory: From 1936 to the present

As has been reported, the role of the University of Barcelona was crucial in the maintenance of meteorological observations in the city during the 19th and 20th centuries. Unfortunately, the Spanish Civil War (1936–1939) meant an abrupt interruption of this activity, and it also meant the closing by force of the observatory boosted by the first SMC, with data from 1922 to 1939. From 1939, meteorology became the direct responsibility of the Spanish Government, under a specific institution that changed names and ministerial dependence several times, from the Air Force to the Ministry of the Environment. But the main problem for this modern period was the frequent relocation of the official observatory within the city, with four changes in only 50 years. The final point is found in 1992, when the official observations in Barcelona were suspended, and El Prat Airport took over as the new official site, at 11 km southwest from the city centre.

Fortunately, the *Reial Acadèmia de Ciències i Arts de Barcelona* (1770), which had promoted meteorological observation among its members but without a specific activity, decided at the beginning of the 20th century to carry out the construction of an astronomical observatory, in which meteorological observation was included as a permanent activity. In 1913, the Fabra Observatory began its records and offers a meteorological series that is still active, located in the nearby hills of the city, and with optimal reliability and continuity. The role of this private academic institution provides a guarantee of continuity for the 21st century.

3. Data collection and digitization

As a result of the historical context described in Section 2, the recovery of meteorological records of the city is an obstacle race, as it requires the consultation of various documentary sources from public and private archives, and they have been preserved into a wide range of formats (i.e. manuscripts, printed reports and journals). Fortunately, thanks to two European Commission funding projects in the late 1990s (IMPROVE and ADVICE), part of the data recovery process had already been addressed, but not for all observed variables (Rodríguez *et al.*, 2001). For over 3 years (2008–2011), SMC, together with the Department of Modern History at the University of Barcelona, resumed the work, completing the digitization already done with the inclusion of other variables, covering some gaps and incorporating other series available in the city that had not been previously reported. As a result, daily temperature series since 1780 were recovered, quality controlled and analysed for homogeneity (Prohom *et al.*, 2012) and a similar approach is presented now to recover the monthly (from 1786) and daily (from 1850) rainfall data for Barcelona. In this article, we present the work to recover the monthly series.

3.1. Sources of data

The observations of the 1780–1827 period of Dr. Francesc Salvà were preserved in original handwritten tables made by the observer himself, at the archive of the *Reial Acadèmia de Medicina de Catalunya* (Francesc Salvà, Tablas Meteorológicas, 3 vols.). The digitization of the data was done in different phases and included the scanning of images of the entire documentary collection, in order to have a backup copy of the originals.

Unfortunately, it was impossible to locate the original documents for the periods corresponding to the doctors who continued after Salvà (1827–1885). Despite the efforts made to locate them in different public and private archives, to date, it is assumed that the documents have been lost. Fortunately, the observers sent the daily data to the local newspaper *Diario de Barcelona*. Consequently, this period was available by consulting the collections of this newspaper for the period 1825–1885 in two public archives in Barcelona. The extraction and digitization of the information was very slow because the data had to be copied from each of the daily copies of the publication.

The observations generated by the University of Barcelona in its initial period in the *Convent del Carme* (1855–1871) were located after a patient investigation, given the lack of documental or bibliographical references. Finally, they were found in the collections of the *Arxiu Històric de la Universitat de Barcelona* (Historical Archive of the University of Barcelona), from which a digital copy of the tables was obtained for the subsequent digitization.

The identification of the documents with meteorological observations made at the new building of the university (commencing in 1882), had a much more complex history. They were generated over an extended period of time, and at the end of the Civil War, along with documents of other Catalan institutions, they were requisitioned and transferred to a deposit near Madrid. After the return of democracy, these documents were returned, with the weather records being the first to return to Barcelona, although in disorder and without being catalogued. Fortunately, they are now well preserved and available to researchers in the *Arxiu de l'Institut Cartogràfic i Geològic de Catalunya*.

Finally, the documentation that presented the fewest problems is that of the Fabra Observatory, as the institution has the capacity of generating and preserving properly its own documentation.

3.2. Metadata

The wide temporal coverage of the records and the great fragmentation in both data sources and placement of the observatories makes difficult the availability of adequate and accurate metadata. This circumstance is particularly critical for the initial period, as the information is quite reduced, limited to brief comments appearing in the local press (*Diario de Barcelona*) when the observers themselves wanted to report an important change. Regarding the observatories installed by doctors, the location is well documented, but very little is known of the type of instruments, their exposition or observation procedures. Rainfall was recorded using rain gauges made by local craftsmen, to which the observer incorporated some type of measurement scale. The first records (1786–1827) were expressed in inches and lines, or lignes, but nothing is known about the basic unit that was used. For this reason, it was necessary to make conversions to different units (Table 1) in order to evaluate them and select the most adequate, taking into account that other instruments were of French origin. Finally, the unit selected was the Paris water-inch, as it offered results similar to available modern precipitation records and in line with the intention of Salvà himself to follow the French pattern of observation (Bonells, 1798).

Table 1. Conversion of different units to Decimal Metric System.

System of measurement	Inch (mm)	Line (mm)
Catalan inch (Barcelona city)	21.61	1.80
French inch (Paris city)	26.15	2.18
Paris water-inch	27.07	2.26
Castile inch (Burgos city)	23.22	1.94

Source: Royal Order in the Council of December 9, 1852 (Basora, 1865).

It is known that in 1827, the observatory was relocated under the supervision of Dr. Vieta. It was organized with utmost care, installing the instruments on the roof of the *Diario de Barcelona* headquarters and imitating the same conditions of the previous location. Although no reference was kept in the metadata, a newspaper chronicle shows that new instruments were also carefully built and installed, with a change from French to Spanish units of measurement (*Diario de Barcelona*, January 1, 1827, p. 1; *Diario de Barcelona*, February 2, 1827, p. 1). For this reason, the conversion was applied to the precipitation corresponding to the Burgos inch, the reference unit in Spain (Table 1). Following this date, a period of observation presented some years with evident anomalies in the data published in the *Diario de Barcelona*. No explanations of the causes of the incidents are given, but it was noted that between 1843 and 1854, there was a frequent absence or repetition of daily and monthly data, probably associated to frequent social riots, in a context of civil war and labour conflicts.

The next doctor–observer, J. R. Campaner, did not leave metadata either. It is known that meteorological instruments were purchased in London, but there are no details on instruments exposure and on observation methods. From this time on, the observations appeared in units of the Decimal Metric System.

The observations made by official services, have less uncertainty in the metadata, especially since 1882 when there is a good knowledge on the type of instrument, its height above ground level and the exact hour of observation. Fortunately, the Fabra Observatory provides good metadata for the more recent period.

Table 2 offers metadata information available for different observation sites described.

3.3. Final composition of the series

As there is no single point or observatory that covers the entire period, the final rainfall series of Barcelona has to be constructed from the different segments available. Figure 1 shows the geographical location of the observatories in Barcelona whose data have been used for the composition of the rainfall series, complemented with additional information in Table 2.

Most of the observatories are placed in the old city for the first 150 years, with little difference in altitude (from 6 to 23 m above sea level, asl), within a horizontal radius of 1.2 km, and being the conditions and the exposure of the instruments quite similar: located on a roof or at the top of a tower. The main change is in 1914, where the series moves to the Fabra Observatory, 4.4 km to the northwest and with a noticeable change in altitude (412 m asl). There are several reasons for having chosen this site:

(a) The Fabra Observatory has no gaps in the series (i.e. the daily series is complete for the entire period and for many variables),
(b) There is a very good knowledge of the metadata,
(c) No changes in the placement of the rain gauges have been reported,
(d) The official observatory in the city changed its location four times, with appreciable microclimatic changes (i.e. the coastline, at the foot of the Tibidabo mountain range and again the city centre). In addition, these changes have also led to changes in instrumentation, observers' skills and exposure.

An attempt was made to continue the last segment of the series with data from the airport of Barcelona, located 11 km to the southwest, with data since 1944. Nevertheless, despite the proximity between the city and the airport, the rainfall regime is quite different. The annual average precipitation is higher in the area of the Llobregat delta, where the airport is located, in relation to surrounding areas, due to the frequent formation of nocturnal surface cold fronts (Mazón and Pino, 2009).

4. Quality control and homogenization

4.1. Quality control

Raw monthly precipitation totals were subjected to a quality test to identify obvious problems and remove suspicious values. Two main checks were used:

(a) Outliers. Monthly rainfall values exceeding five times the interquartile range.
(b) Zero monthly values. In order to distinguish among months with no precipitation from those with no observation, the values where compared, when possible, with the observed values at nearby stations, and most correlated (Figures 2 and 3 show the series used at this step and during the homogeneity analysis.). A value is flagged as suspicious if at least 75% of the available series reports at least 10 mm of difference.

From the analysis, 15 monthly values were identified as erroneous and were finally eliminated, these being mainly located in the 1844–1854 period and associated with continuous repetitions of monthly values appearing in the *Diario de Barcelona* as a result of the social disturbances and public insecurity prevalent in the city.

4.2. Homogeneity analysis

Long-term instrumental series of climate variables are often affected by abrupt changes caused by climatic and/or non-climatic factors. The aim of homogenization techniques (i.e. procedures combining detection and correction) is the removal (or at least the reduction) of the non-climatic signal affecting the time series under investigation (Aguilar *et al.*, 2003). The large number of different techniques and the need for a realistic comparative study led to a coordinated European initiative, the COST Action Advances in Homogenization Methods of Climate Series (Action COST ES0601, 2011; Venema *et al.*, 2012). As a result of the action, the HOMER method for the homogenization of climate series was generated (Mestre *et al.*, 2013) and has been used in this study.

HOMER is an interactive and semiautomatic method that includes the best features of other existing methods such as PRODIGE (Caussinus and Mestre, 2004), ACMANT (Domonkos, 2011) and a joint-segmentation method initially developed by biostatisticians in the field of DNA segmentation (Picard *et al.*, 2011). The results of several experiments, performed blindly during the COST action, validated these approaches as being among the best methods for testing the homogeneity of annual or monthly climate time series (Venema *et al.*, 2012).

In order to have an overview of the HOMER method, a summary of the different steps is shown in a task flow chart (Figure 4) and described in detail in the following subsections.

4.2.1. Reference rainfall series

HOMER is a relative homogenization method which requires neighbouring series for computation. As a consequence, the first step was to identify monthly rainfall reference series long enough to test the Barcelona series and with a good correlation. Figure 2 shows their main characteristics, while Figure 3 presents their geographic distribution and coefficient of correlation with the Barcelona series.

Most of the series were collected from well-known data sources: SMC database for the Catalan and some French series, AEMET (Agencia Estatal de Meteorología) database and Almarza *et al.* (1996) for the Spanish series and several other sources from international databases (GHCN V.2, Peterson and Vose, 1997) or research projects outputs (Auer *et al.*, 2005; IMPROVE, Camuffo

Table 2. Main geographical and instrumentation details on the observatories used for the final composition of the rainfall series.

Observatory	Period	Altitude asl (m)	Distance from the previous site (m)	Rain gauge placement/ type/units/ ground-level altitude (m)
1. Petritxol street	July 1786–January 1827	8		On a roof/unknown/French system (Paris)/∼30
2. Llibreteria street	February 1827–February 1854	15	410	On a roof/unknown/Castilian system (Burgos)/∼30
3. Banys Nous street (Royal Academy of Medicine, RAM)	February 1854–July 1876	8	290	On a terrace/unknown/mm/∼10
4. Carme street (provisional University)	August 1876–November 1880	15	540	On a roof/Hervéangon/mm/∼30
5. Zurbano street	December 1880–December 1882	6	740	On a roof/unknown/mm/∼30
6. University of Barcelona (definitive building)	January 1883–December 1913	23	1240	On a terrace/Hervé Mangon/mm/25
7. Fabra Observatory	Since January 1914	412	4400	In a garden/Hellmann/mm/1.5

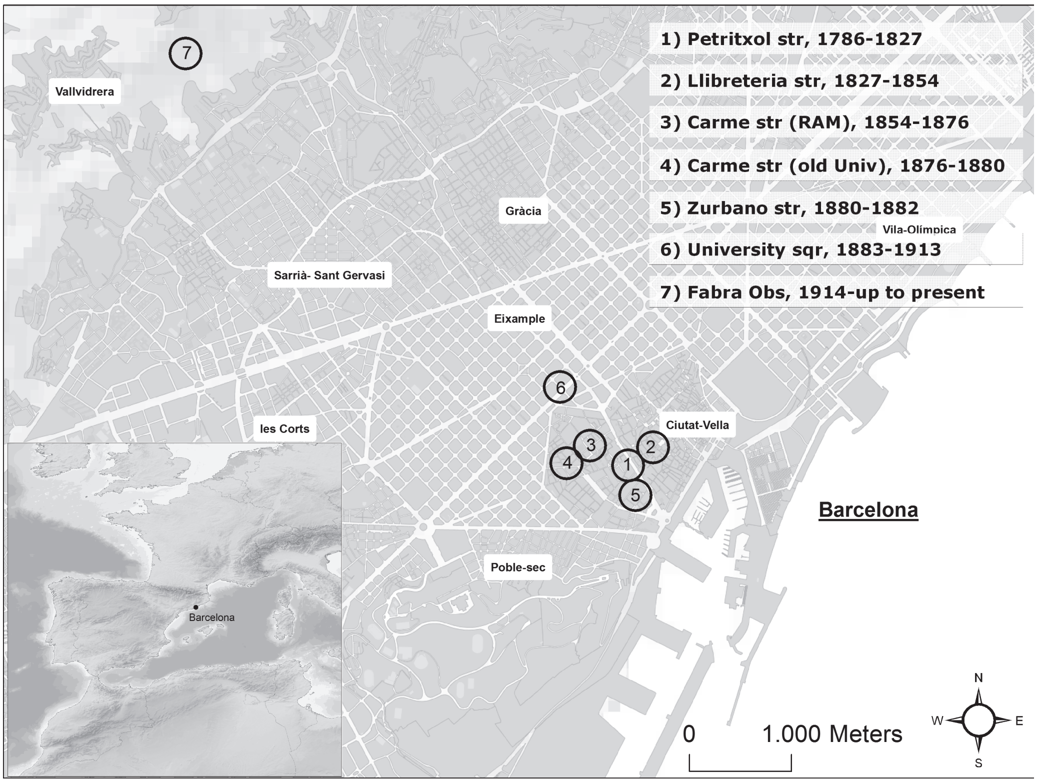

Figure 1. Geographical location of Barcelona within the European continent and, in detail, the observatories sited in the city and the segment of data used for the composition of the final series.

and Jones, 2002; ADVICE, Jones *et al.*, 1999). The 'BCN 2' series in Figure 2 corresponds to a composition of the series made up of observations made by Llorenç Presas (1849–1874) and Joan Montserrat (1881–1885) both in the downtown of Barcelona. Additionally, some French series were digitized for the first time for this study from old publications extracted from GALLICA website (http://gallica.bnf.fr): Nimes, Montpellier, Perpinyà, Béziers and St-Hippolyte-de-Caton (Raulin, 1876, 1894; Roche, 1882; Angot, 1916). The existence of these sources was supplied by the Directorate of Climatology of Météo-France (Sylvie Jourdain, pers. comm.). The series are composed from raw data, as the other reference series used in the analysis, and basic metadata information is collected from all of them (i.e. relocation and observer changes).

4.2.2. *Break-point detection phase*

Through HOMER, detection of inhomogeneities relies on several hierarchical and iterative steps: pairwise detection, joint analysis and the ACMANT approach. For detection, the entire set of series shown in Figures 2 and 3 was used.

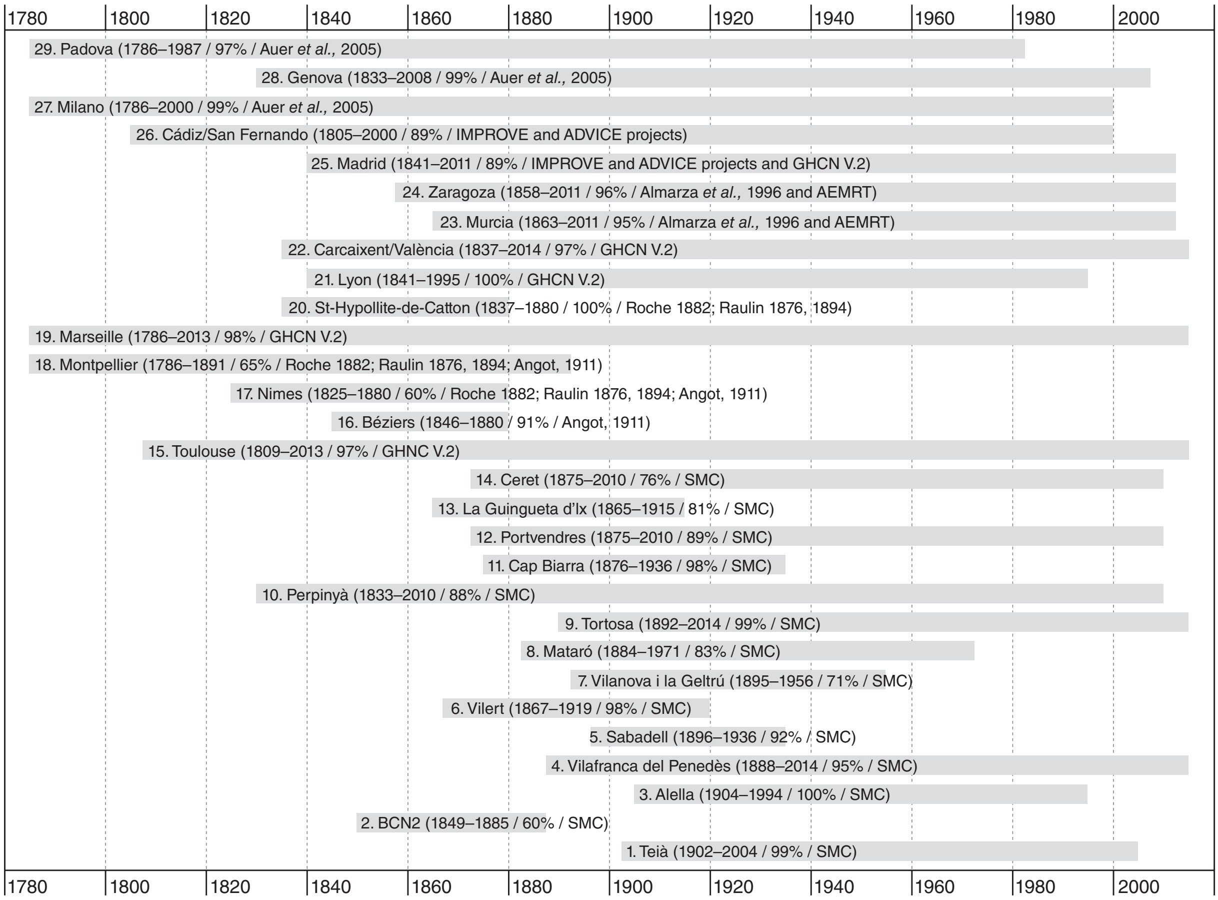

Figure 2. Reference rainfall series used during the quality and homogeneity analysis. The shadowed rectangles show the maximum temporal coverage of each series and in their interior its name, starting and final years, percentage of data available in that interval and data sources.

During pairwise strategy, the candidate series (here Barcelona) is compared to its neighbours by computing series of differences and these difference series are then tested for discontinuities. At this step, if a detected change point remains constant throughout the set of comparisons, it can be attributed to this candidate series. In this study, we used the criterion suggested by Kuglitsch *et al.* (2009) where a break point is assumed as real whether more than three break points are detected within two consecutive years. As a result, a first list of likely break points was revealed at this phase and mostly supported by metadata: 1826, 1840, 1875 and 1914 and an additional suspicious one around 1895 (Figure 5).

To improve the detection phase, an additional approach is run by HOMER using the overall two-factor model, which allows the analysis and correction of the whole set of series: the joint-detection phase. Here, *multiseg* function determines automatically a number of change points, which in our study were coincident with the first list suggested by the pairwise step and confirmed the 1895 break point (Figure 6).

Finally, ACMANT helps finding changes with strong seasonal behaviour and is applied after the correction phase as works with pre-homogenized series. In this study, all the breaks previously reported were confirmed by ACMANT.

4.2.3. *Adjustment phase*

Once break points were determined, the correction phase was applied using the best-correlated time series of the reference series (>0.50 and computed removing the yearly cycle) and ensuring that the whole period was covered by at least three series. A log ratio multiplicative correction was applied at this point, using a two-factor analysis of variance (ANOVA) model that significantly improves the results compared to other methods (Domonkos, 2013). The ANOVA approach also allowed the restitution of months or years without data, especially those located during the 1844–1854 period.

Overall, the analysis of the yearly adjustments shows magnitudes that vary between factors (homogenized data divided by original values) of 0.62 and 1.21 (Figure 7). The larger adjustments are located in the period 1827–1843 when the availability of complete data (yearly sums) is poor due to a large fraction of gaps. As the evaluation of the adjustments is based on statistical significance, the size of the detectable inhomogeneity is dependent on the correlation between the candidate series and the available reference series and on the density of the measuring network. In contrast, for the past 160 years (since 1856) the corrections are not very large. Equally, for the last correction in 1914, the size of the adjustment from the city centre segment to the Fabra Observatory regime is

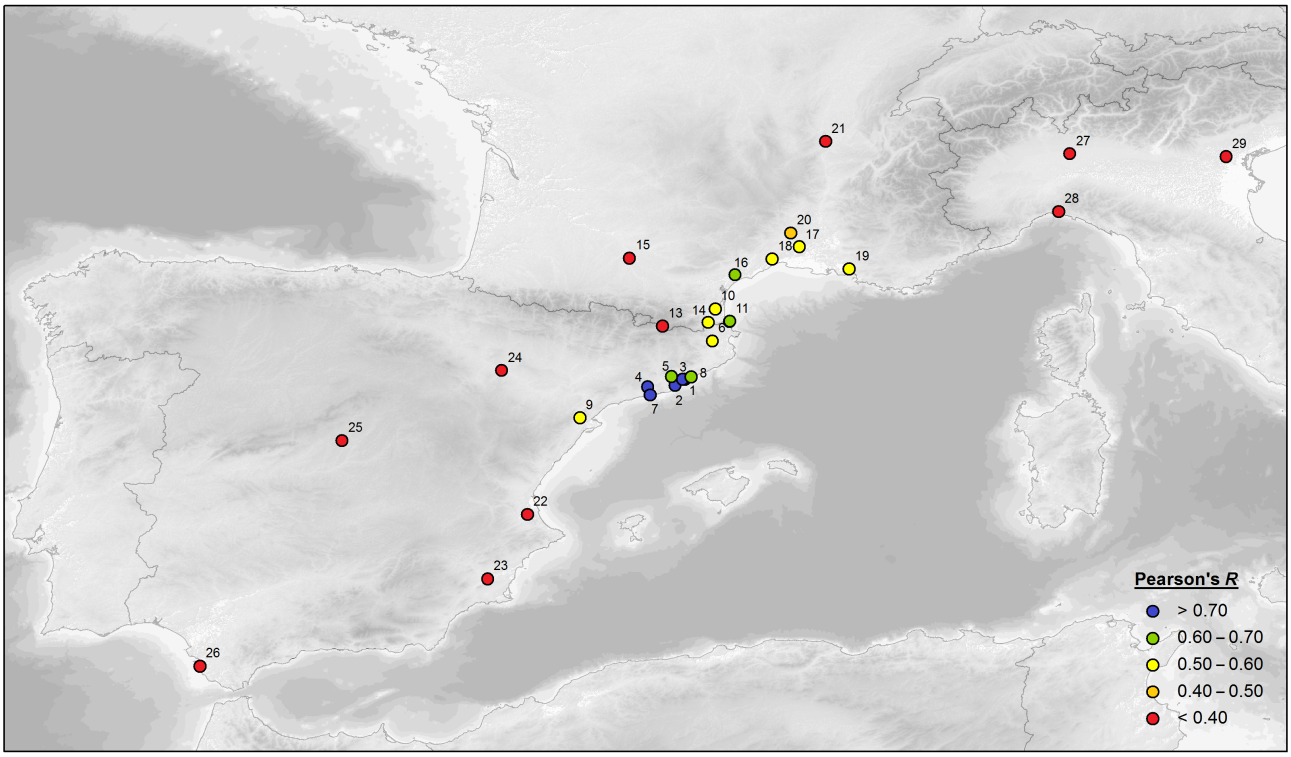

Figure 3. Spatial distribution of the climatic series used during the process of quality control and homogeneity (see Figure 2), indicating the coefficient of annual correlation with the Barcelona series through a colour code.

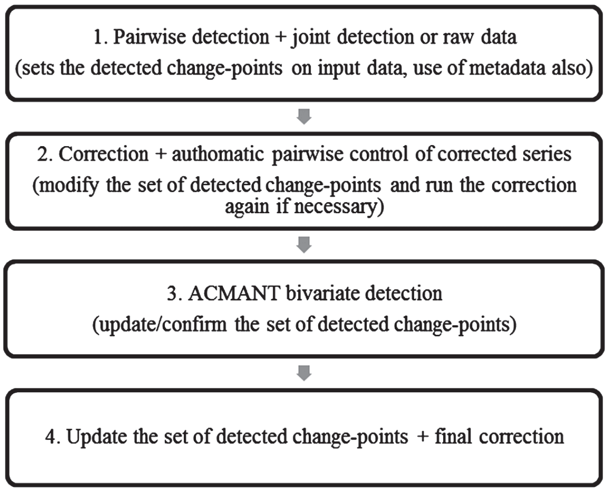

Figure 4. Tasks flow chart of HOMER applied for the rainfall precipitation series of Barcelona.

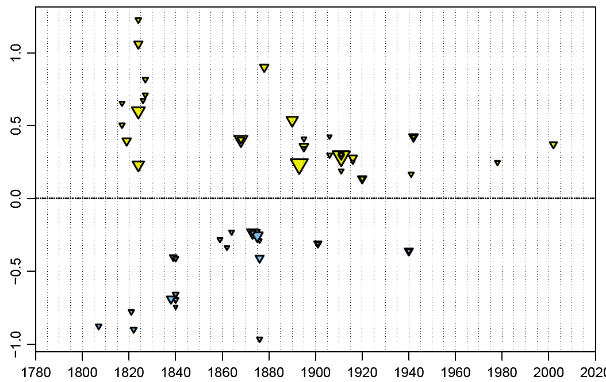

Figure 5. Results of pairwise comparison run in Barcelona rainfall series. The value on the y-axis is the amplitude of change points. An accumulation of several triangles around a same year (at least three) denotes a likely break point.

robust, as it coincides with that reported by comparison of Fabra with other rainfall stations located in the city (not shown).

Finally, it is worth mentioning that the homogenized series presented in this study differs from the results presented by Camuffo *et al.* (2013), which used a preliminary version of the precipitation series in Barcelona, without taking into account the new digitized data provided now in this study. In addition, Camuffo *et al.* (2013) used an absolute homogenization method (instead of the relative one used in this study) to detect and correct inhomogeneities in the series, which has possibly led to an overestimation of the adjustment factors during the EIP period due to the tendency towards negative anomalies of the precipitation during this period as detailed in the next section.

5. Time evolution and trends of the homogenized series

Figure 8 shows the annual precipitation series from 1786 to 2014. Its mean value for the whole period is 592.5 mm, with a standard deviation of 152 mm. The maximum is recorded in 1971 (1123 mm) and the minimum in 1817

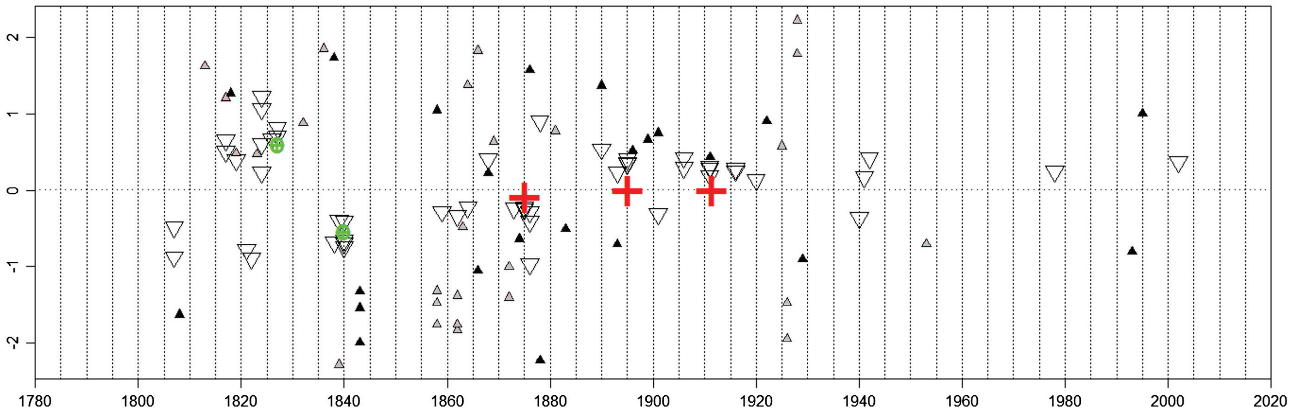

Figure 6. Screen capture of HOMER outputs: date (x-axis) and amplitude (y-axis) of change points detected on the whole set of pairwise comparisons: annual comparison (blank), winter (black) and summer (grey) triangles. Automatic joint-detection results are indicated by rounded crosses symbols, while big crosses indicate user's intervention.

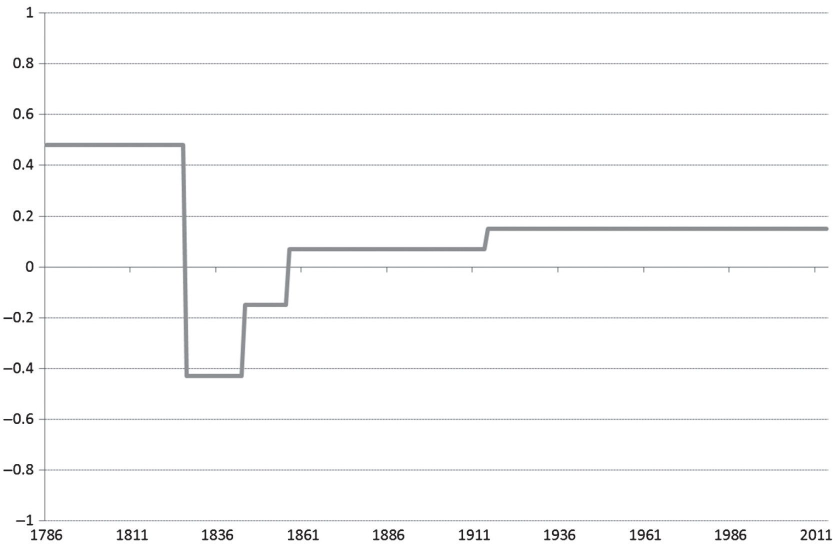

Figure 7. Yearly adjustment factor of the Barcelona rainfall series (homogenized divided by original data).

(216 mm). Table 3 shows a list with the ten driest and wettest years observed in Barcelona for the whole period. Regarding its decadal variability, the annual series starts with a period without relevant variations until the early 1800s, followed by a strong decrease in precipitation from the 1810s to the 1840s. As an example, during the period 1806–1841 (36 years) more than 80% of the values are below the climatological mean. Subsequently, there is strong increase and a change to positive anomalies of precipitation in the 1840s and 1850s, followed by a strong decrease during the 1860s. Afterwards, there are no relevant multi-decadal variations of the precipitation in Barcelona, and only a slight decrease (increase) from the early (mid) to the mid (late) 20th century is worth mentioning.

The overall linear trend over the entire period is positive and significant ($p < 0.05$) as estimated by the Mann–Kendall test. Specifically, there is an increase of 4.7 mm per decade, which implies an increase of 107.2 mm (18.1%) over the whole study period. Nevertheless, the significant increase over the entire period is due to the tendency towards lower values of precipitation during the first half of the 19th century. Thus, linear trends since the mid-19th century are not significant, as shown in Table 4, which includes the linear trends on annual and seasonal basis applied over the entire 1786–2014 period, as well as different sub-periods.

As far as seasonal series are concerned (Figure 9), precipitation in winter has a mean value of 117 mm, with a standard deviation of 75 mm. The minimum is observed in 1825 with no precipitation recorded during the whole season. The lack of precipitation is in agreement with the reconstructed sea level pressure (SLP) anomaly field (Luterbacher *et al.*, 2002) of this year, which highlights the prevalence of strong anti-cyclonic conditions over the Iberian Peninsula (Figure 10(a)). The maximum in the winter series is reached in 1944 (326 mm), but during the EIP, the three consecutive years from 1839 to 1842 can be highlighted, as they show very positive values. As in the annual series, the winter shows a strong decrease in precipitation from the early 1800s to the 1830s. Subsequently, there is a tendency to increase from the 1840s

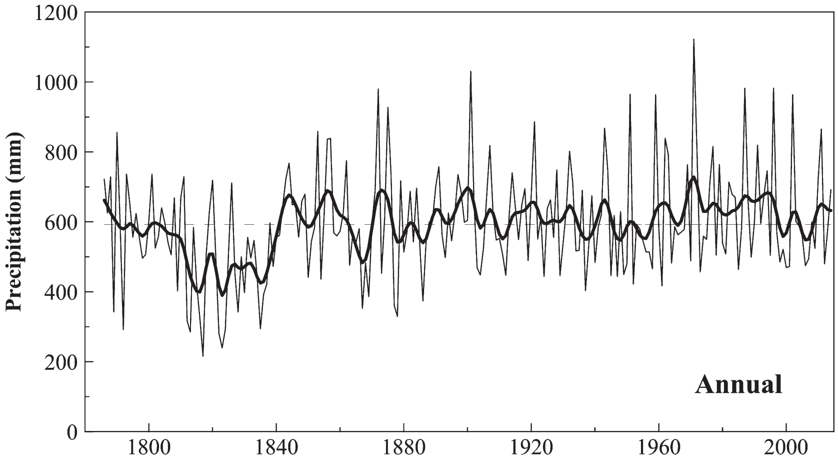

Figure 8. Homogeneous annual rainfall series for Barcelona (solid line) from 1786 to 2014, together with an 11-year low-pass filter (bold line). The horizontal dashed line shows the mean precipitation in Barcelona.

Table 3. Top ten wettest and driest years in Barcelona during the period 1787–2014.

Wettest years		Driest years	
Year	Rainfall (mm)	Year	Rainfall (mm)
1971	1122.7	1817	215.6
1901	1030.6	1823	239.4
1996	982.4	1822	280.5
1987	980.0	1813	285.3
1872	964.7	1792	291.8
1951	963.8	1824	292.8
1959	963.5	1835	294.6
2002	927.4	1812	317.7
1875	886.3	1816	325.0
1821	867.8	1878	329.2

Table 4. Annual and seasonal precipitation trends in Barcelona over the period 1787–2014 and different sub-periods.

Period	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
1787–2014	+4.9*	−1.9*	+1.3	+1.1	+0.5
1787–1840	−34.2*	−2.2*	−8.0	−2.9	−23.7*
1841–1900	+6.2	+4.4	−6.7	+1.4	−5.6
1901–1960	−7.5	−4.5	−2.5	+3.5	−3.8
1961–2014	−7.1	−3.6	+4.3	−7.5	−0.5

The linear trends of the series were calculated by means of linear least squares and the values are expressed as mm decade^{-1}.

*Indicates trends with significance level higher than 95% as estimated by the Mann–Kendall nonparametric test.

to the early 20th century, with no relevant multi-decadal variations afterwards. The linear trend over the whole period is positive and significant ($p < 0.05$), as in the annual series, with an increase of 1.9 mm per decade, which implies an increase of 44.0 mm (37.6%) over the whole study period. Again, as in the annual series, the significant increase is due to the lower values of the precipitation during the first half of the 19th century and the linear trends since the mid-19th century up to the present are not significant (Table 4).

Spring series has a mean of 155.8 mm and a standard deviation of 70 mm, with a maximum of precipitation in 1977 (341 mm) and a minimum in 1893 and 1823 (26 mm). The SLP anomaly map for spring 1823 confirms strong positive values over the western part of the Iberian Peninsula (Figure 10(b)), which is in line with the low values of precipitation observed in Barcelona. The most relevant feature of spring series during the EIP is that it shows a slight decrease from the early 1800s to the 1820s, which is less evident than the reported decrease observed on an annual basis. Subsequently, there is an increase until the mid-1850s with a strong decrease afterwards during the 1860s. The linear trend over the whole period is not significant.

In summer, corresponding to the driest season in Barcelona, the series shows a mean precipitation value of 100.9 mm with a standard deviation of 57.5 mm. In this season, the period prior to 1850 is characterized by a tendency to negative anomalies but there is no evidence of a drop of the precipitation as in the other seasonal series. The maximum is reached in 1976 (358 mm) and the minimum in 1928 and 1791 (5 mm). No significant trend is observed in the entire study period.

Finally, autumn is the wettest season in Barcelona having an average precipitation of 216.5 mm and a standard deviation of 95.4 mm, with a maximum and minimum in 1987 (499 mm) and 1869 and 1981 (51 mm), respectively. The time evolution shows the strongest drop in the records during the first half of the 19th century but no significant trend if the whole study period is considered. During the period 1806–1842 (37 years) only 6 years recorded more precipitation than the climatological mean value. It is worth noting that in the late 1830s and early 1840s, there is the largest persistence of low values, with a sharp increase after 1843.

With this last feature, the temporal homogeneity of the series can be called into question, as it appears that the break located in the early 1840s may not have been properly adjusted. Nevertheless, a comparison of the autumn precipitation series in Barcelona and surroundings stations

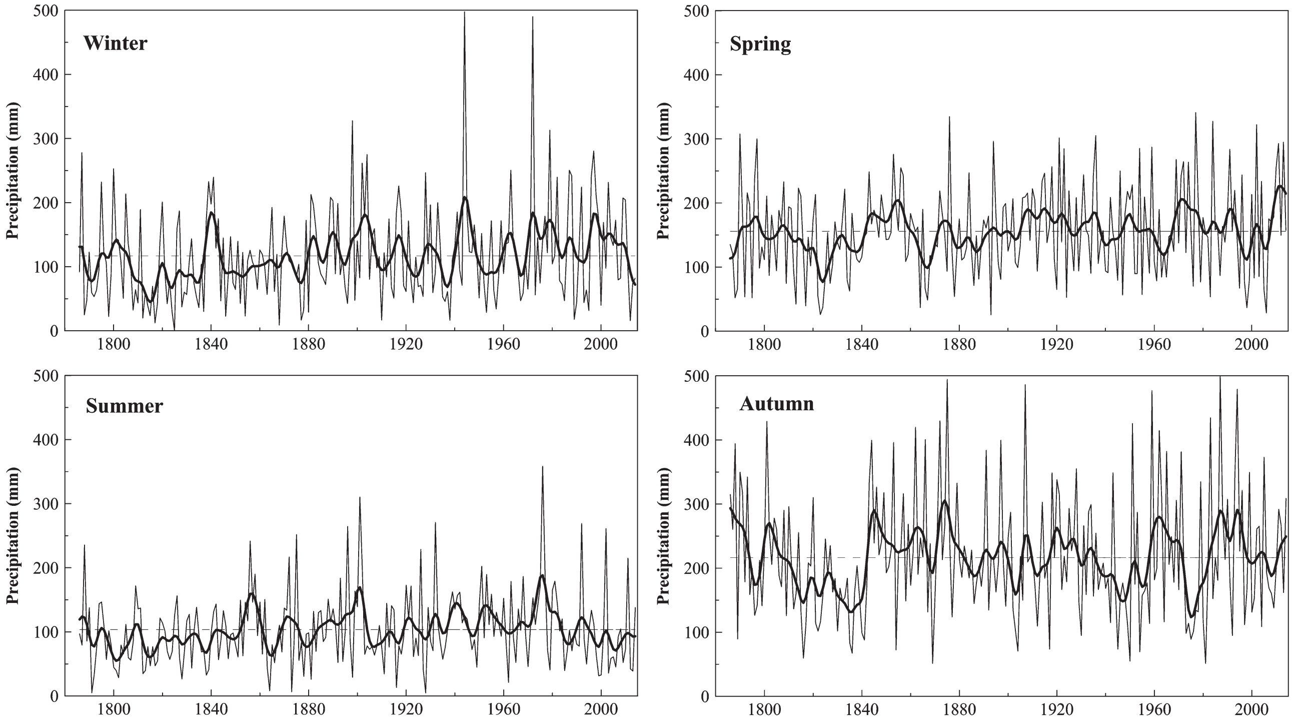

Figure 9. Homogeneous seasonal rainfall series for Barcelona (solid line) from 1786 to 2014, together with an 11-year low-pass filter (bold line). The horizontal dashed line shows the mean precipitation in Barcelona.

with data over this period show that the signal is real and not an inhomogeneity. Thus, for example, Figure 11 shows the Barcelona autumn series and a set of reference series during the period 1786–1880. This reference series has been constructed with four stations (i.e. Perpinyà, Montpellier, Marseille and Nimes, Figures 2 and 3) and was weighted using the correlation coefficients between the Barcelona series and these four series. The series were converted into relative anomalies before the averaging in order to avoid discontinuities due to the different period of each series and mean precipitation amounts. Overall, both series in Figure 11 highlight a strong increase in precipitation in the early 1840s after a period of low precipitation, which enables us to argue that the temporal homogeneity of the Barcelona series is not jeopardized during this period.

Overall, from the annual and seasonal series shown in Figures 8 and 9, it is clear that there is a distinct drop in the precipitation series of Barcelona during the early 19th century, which highlights a mega-drought lasting more than two decades and with no changes of similar magnitude since the mid-19th century up to the present. Taking into account the uncertainties in the instrumentation and metadata (e.g. units of measurement, changes in instrumentation, etc.), it would be considered reasonable to think that one explanation for these negative anomalies is due to a lack of temporal homogeneity in the series during the EIP, as already discussed in the previous paragraph. However, as shown before in Figure 11, and also in Figure 12 which shows the reconstructed precipitation anomalies over Europe during the period 1808–1835 (Pauling *et al.*, 2006), it is clear that a period with drier conditions prevails during these years in southern Europe, in line with the instrumental precipitation records in Barcelona. Thus, the annual reconstructed precipitation records by Pauling *et al.* (2006), from 1786 to 1880 and for the grid point over Barcelona show a slight overestimation of the mean values and an underestimation of the variability as compared to the observations (not shown), but the standardized time series has good agreement on interannual and decadal time scales (Figure 13).

It is worth noting that this reconstructed precipitation data set by Pauling *et al.* (2006) did not use instrumental data from Barcelona (or other locations in Spain) during the EIP, as only documentary indices were considered (see Figure 1 in Pauling *et al.*, 2006). In this regard, rogation ceremonies and other documentary sources in Spain have previously shown the trend towards drier conditions during these years of the early 19th century (Martin-Vide and Barriendos, 1995; Trigo *et al.*, 2009; Machado *et al.*, 2011; Dominguez-Castro *et al.*, 2012; Fernández-Fernández *et al.*, 2015), supported by other testimonials of dry conditions in different regions of Africa during this period (Nicholson, 2000; Nicholson *et al.*, 2012). All these indications support the temporal homogeneity of the instrumental records from Barcelona during the EIP, as well the reliability of the mega-drought period in Barcelona from the 1810s to the 1830s.

Overall, this mega-drought observed in Barcelona during the early 19th century happened during the solar Dalton Minimum and a period of high volcanic activity, such as the large volcanic eruptions occurring in 1809 (unknown), 1815 (Tambora), 1831 (Babuyan Claro) and 1835 (Cosiguina) (Gao *et al.*, 2008; Anet *et al.*, 2014). It is well known that drier conditions prevail in southwestern Europe in

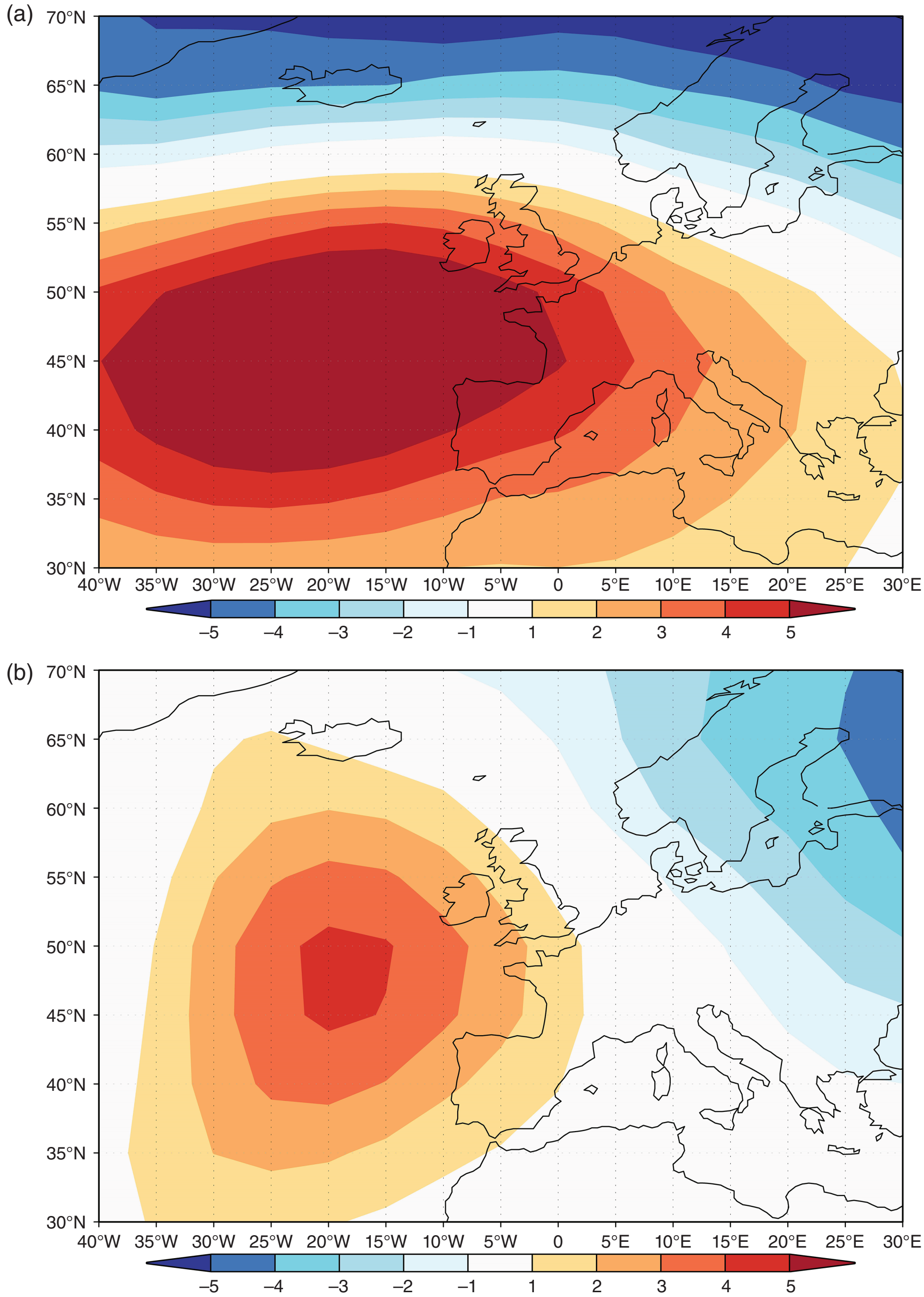

Figure 10. Reconstructed SLP anomalies (hPa) for (a) winter 1825 and (b) spring 1823 with respect to the 1750–1850 reference period. The SLP fields have been extracted from Luterbacher *et al.* (2002).

wintertime after large tropical eruptions that induce a North Atlantic Oscillation-like (NAO) circulation pattern (Robock, 2000; Fischer *et al.*, 2007; Luterbacher and Pfister, 2015). Other studies support these findings, reporting an increase in the frequency of clear-sky days during this season in Barcelona and following the Tambora eruption (Auchmann *et al.*, 2013). More recently, Anet *et al.* (2014) have shown that the high volcanic activity during this period is the main driver of the precipitation anomalies during the Dalton Minimum (i.e. more relevant than solar forcing), with a significant decrease in precipitation in southern Europe due to the widening of the Hadley cell.

6. Concluding remarks

The availability of instrumental climatic records is vital for the accurate reconstruction of variability and climatic change on a regional scale. The Mediterranean area, especially exposed to these two phenomena, attracts a large share of attention and any improvement in the quality and quantity of available climatic series is of great value. In this regard, the rainfall series of Barcelona recovered in this study from July 1786 means having continuous monthly records of great quality for more than 225 years, the longest and most continuous of the Iberian Peninsula.

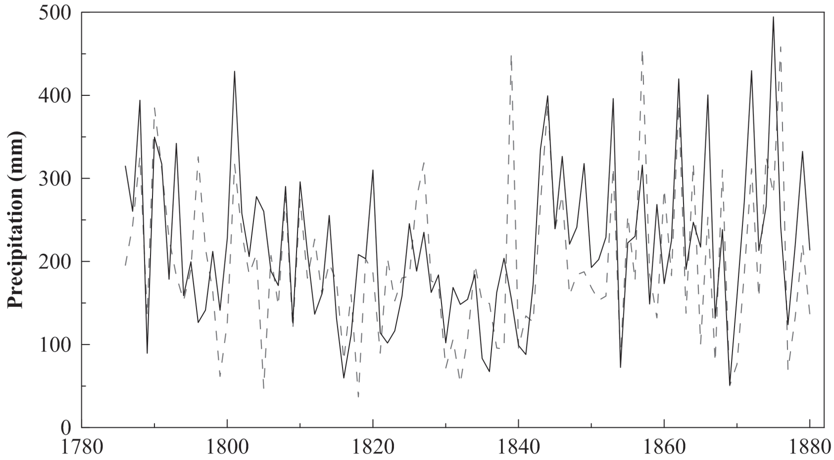

Figure 11. Autumn precipitation in Barcelona (black solid line) and a reference (red dashed line) series constructed with data from Perpinya, Montpellier, Nimes and Marseille during the 1786–1880 period. Both time series highlight the tendency to decrease during the first half of the 19th century, with a subsequent increase in the early 1840s.

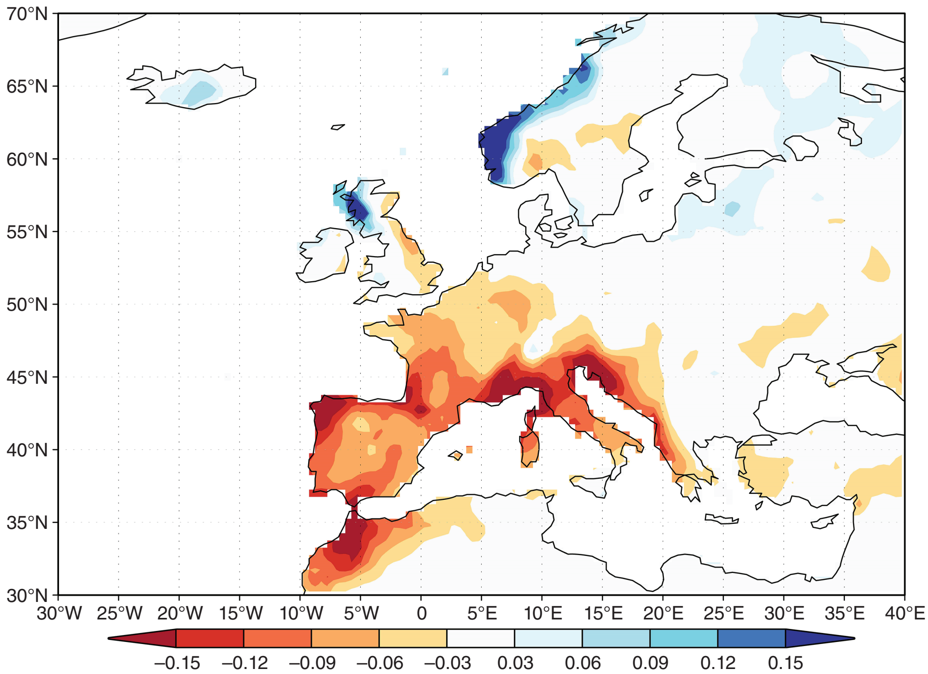

Figure 12. Reconstructed precipitation anomalies for the period 1808–1835 with respect to the 1750–1850 reference period. The precipitation fields have been extracted from Pauling *et al.* (2006) and the anomalies are expressed as mm day^{-1}.

Monthly series has been evaluated on the basis of criteria of relative homogeneity, applying HOMER methodology recommended by the COST Action ES6001 for the detection of inhomogeneities and to determine their adjustment. The relative nature of the homogeneity method requires series contemporary to the Barcelona series, an aspect especially difficult to fulfil for the period prior to 1850. In this regard, the identification and recovery of different climatic series in the French Mediterranean coast and with an acceptable correlation (>0.6) has improved the capacity for the detection of the break points and adjustment of the final series. Despite the scarce metadata information, the result of the homogeneity testing reveals the existence of five non-homogeneous periods associated, mostly, with changes in the location of the observatory. The principal break point was expected to be the last one, associated with the change of location to the Fabra Observatory located at 412 m asl. Despite this, the notable presence of nearby climatic series with a very good correlation (>0.85) has allowed satisfactory adjustment of the series.

It is worth noting that the early period of the series can still be affected by remaining inhomogeneities due to few reference series available, as well as their distance from Barcelona. Nevertheless, the homogenized monthly series of Barcelona had shown a consistent picture during this early period when compared with observed and reconstructed precipitation in the Western Mediterranean basin,

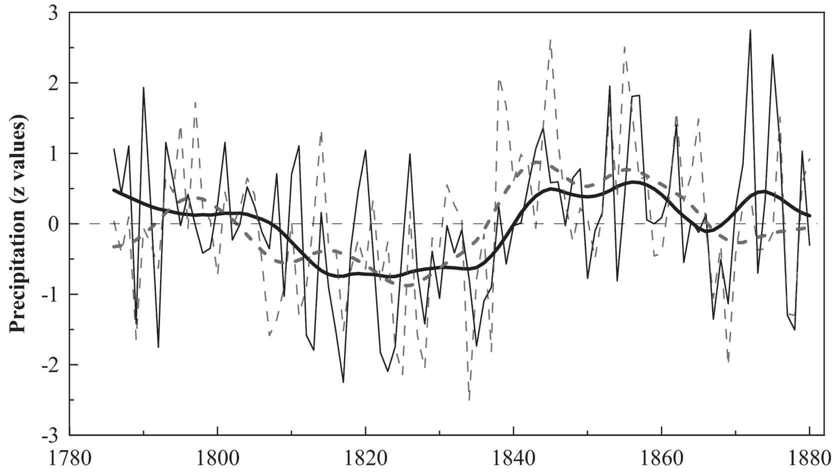

Figure 13. Annual precipitation in Barcelona from observations (black solid thin line) and reconstruction by Pauling *et al.* (2006) as extracted for the closest grid series (red dashed thin line) from 1786 to 1880, together with an 11-year low-pass filter (thick lines). The series have been normalized with the mean values and standard deviation of the period 1786–1880. The horizontal dashed line shows the zero score value.

which supports the reliability of the homogenization procedure performed in this study.

Further research is needed in order to rescue other long-term measurements of precipitation over the Western Mediterranean, which can help to reduce the uncertainties of the relative homogenization of the Barcelona series performed in this study. In this regard, Brunet *et al.* (2013) have recently been able to identify a wide range of archives in the Mediterranean basin with instrumental series that are expected to be rescued, and they would allow substantial improvement of the climatic information of the past. These new records would offer, as the Barcelona series does, a unique opportunity to examine the natural variability of the climate in the Mediterranean region.

The analysis of the Barcelona rainfall series identifies a significant overall trend towards an increase of annual (of approximately 18%) and winter precipitation, which in both cases is supported by the dry character of the initial period up to the middle of the 19th century. This behaviour is not maintained for other more recent sub-periods and since 1900 the behaviour is the opposite, with negative tendencies on an annual scale and for winter, although these are not significant. This recent pattern has been detected by other studies centred on the Iberian Peninsula. Thus, de Luis *et al.* (2009) identify annual decreases of around 40 mm decade^{-1} for the period 1950–2000, and similar trends for winter are reported by Rodrigo and Trigo (2007) and Lopez-Bustins *et al.* (2008).

For the entire series, the records permit the identification of notable periods in which the precipitation in Barcelona was significantly below average. The period between 1808 and 1835 shows a predominance of dry years without precedent in the instrumental era. Monthly rainfall records in the French Mediterranean coast (e.g. Marseille, Montpellier and Nimes), as well as reconstructed precipitation in the Western Mediterranean basin, corroborate the extraordinarily dry behaviour in this period, especially during autumn, and limit the initial uncertainty of the records recovered in Barcelona. The comparison of these extremes with different proxy records would support the conclusions and requires a future detailed analysis on its causes (e.g. solar activity and volcano activity) and consequences.

The consequences of the repetition of a similar event in the current socioeconomic context are noteworthy. With a notable population increase (of 86% in the Mediterranean area since 1950, according to Sumner *et al.*, 2001), the demand for water resources has increased exponentially during the 20th century, due especially to the requirements of the agricultural and tourism sectors. Conditions such as those recorded at the beginning of the 19th century, if repeated, would be alarming for their impact on the normal performance of human activities and also in view of the foreseeable ecological consequences.

Finally, the authors note that for a better dissemination, the homogenized monthly series developed in this study is freely available to the research community in the web pages of the Department of Climatology of the Meteorological Service of Catalonia (www.meteo.cat) and Research Gate (https://www.researchgate.net/publication/282798379_Monthly_rainfall_series_for_Barcelona_%281786-2014%29) the NOAA Paleoclimatology Historical Datasets (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets), as well as on request to the author (mprohom@meteo.cat).

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