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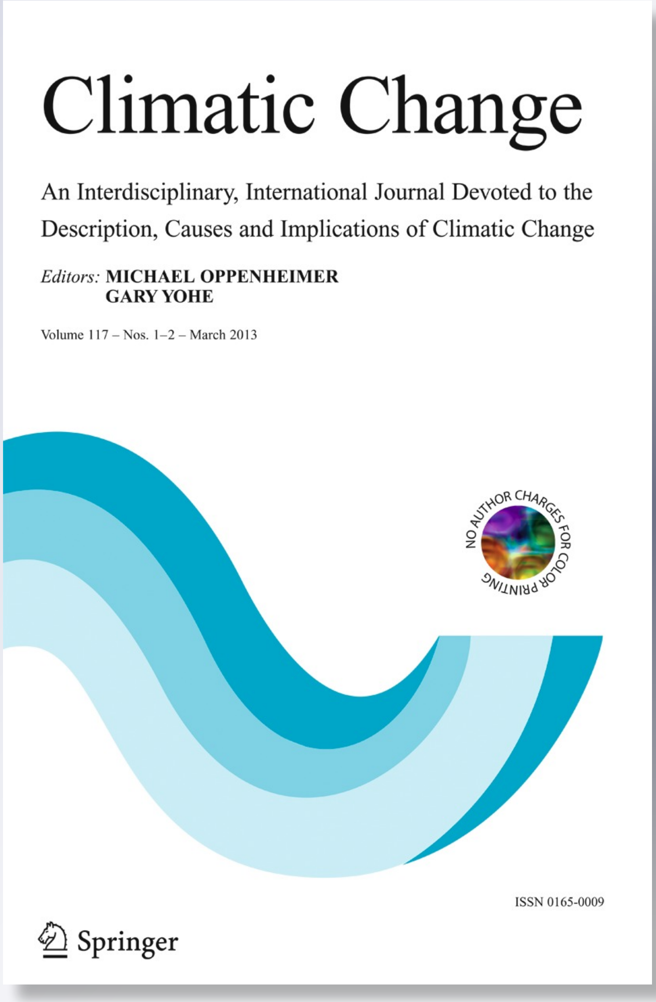
**Climatic Change**
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

ISSN 0165-0009
Volume 117
Combined 1-2

Climatic Change (2013) 117:85-101
DOI 10.1007/s10584-012-0539-9



Springer

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# Western Mediterranean precipitation over the last 300 years from instrumental observations

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Received: 2 August 2010 / Accepted: 26 June 2012 /

**Abstract** The paper reports the results of the analysis of the 14 longest precipitation instrumental series, covering the last 300 years, that have been recovered in six subareas of the Western Mediterranean basin, i.e., Portugal, Northern and Southern Spain, Southern France, Northern and Southern Italy. This study extends back by one century our knowledge about the instrumental precipitation over the Western Mediterranean, and by two centuries in some specific subareas. All the time series show repeated swings. No specific trends have

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**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-012-0539-9) contains supplementary material, which is available to authorized users.

D. Camuffo (✉) · C. Bertolin
National Research Council of Italy (CNR), Institute of Atmospheric Sciences and Climate (ISAC), Corso Stati Uniti 4, 35127 Padova, Italy
e-mail: d.camuffo@isac.cnr.it

N. Diodato
MetEROBS – Met European Research Observatory, Via Monte Pino s.n.c, 82100 Benevento, Italy

C. Cocheo
Salvatore Maugeri Foundation IRCCS, Padua, Italy

M. Barriendos
Department of Modern History, University of Barcelona, Barcelona, Spain

F. Dominguez-Castro
Department of Physics, University of Extremadura, Badajoz, Spain

E. Garnier
Institut Universitaire de France (Paris), Saclay, France

E. Garnier
Centre de Recherche d'Histoire Quantitative (UMR CNRS- University of Caen), Caen, France

M. J. Alcoforado
Centre for Geographical Studies, University of Lisbon, Lisbon, Portugal

M. F. Nunes
History and Philosophy of Science Research Unit, University of Évora, Évora, Portugal

been found over the whole period, except in a few cases, but with modest time changes and sometimes having opposite tendency. The same can be said for the most recent decades although with some more marked departures from the average. The correlation between the various Mediterranean subareas is generally not significant, or almost uncorrelated. The Wavelet Spectral Analysis applied to the precipitation identifies only a minor 56-year cycle in autumn, i.e., the same return period that has been found in literature for the Sea Surface Temperature over North Atlantic. A comparison with a gridded dataset reconstruction based on mixed multiproxy and instrumental observations, shows that the grid reconstruction is in good agreement with the observed data for the period after 1900, less for the previous period.

## 1 Introduction

Although the rain gauge was invented in 1639 by Father Benedetto Castelli, a pupil of Galileo (Castelli 1639), to measure the precipitation on the Trasimeno lake and to draw the first hydrological balance, its use was limited or stopped by the Inquisition after the trial for heresy and the sentence against Galileo in 1633. When in 1667 the Inquisition closed the scientific academy, known as *Accademia del Cimento* founded by the Grand Duke of Tuscany Ferdinand II and his brother Prince Leopold de' Medici, a long pause followed for any scientific activity, including meteorological observations. After the dramatic ending of the *Accademia del Cimento*, weather measurements were made but not regularly published, except for medical considerations. The situation improved during the papacy of Pope Clement XI (1700–1721), born Giovanni Francesco Albani. Regular instrumental observations of temperature and precipitation were started in 1716, simultaneously recorded in Padua by Giovanni Poleni, Bologna by Jacopo Bartolomeo Beccari and Naples by Nicolò Cirillo. The situation was better in France, where under the protection of the *Académie Royale des Sciences*, established in Paris in 1666, several observers were able to publish their readings, or at least a summary of them.

A list of the instrumental observations used in this work is reported below and summarized in Online Resource 1 and Online Resource 2 based on 14 individual stations distributed over 10°x 26° latitude x longitude that is a relatively high density, especially for the 18th century, because a large offshore region is included. Most of these time series have been recovered and are presented here for the first time. They extend back by two centuries the period in which accurate instrumental precipitation observations are available. This is an important contribution especially because it gives the possibility of calibrating precipitation reconstruction models mainly based on proxy indices. These models suffer for the uncertainties intrinsic of the specific proxy methodologies used in the reconstruction.

## 2 Instrumental stations in the Western Mediterranean Basin

### 2.1 Portugal

In Portugal (PT), the contact with other European Academies (particularly the *Academia Meteorologica Palatina,* Mannheim, and the *Société Royale de Médecine*, Paris) encouraged the collection of instrumental observations. They were usually compiled in short series of temperature, rainfall and atmospheric pressure, occasionally including qualitative information about the "weather" and wind speed or direction. The *Royal Academy of Sciences*, founded in Lisbon in 1779, fostered the addition of meteorological observations to the usual astronomic ones.

The earliest series of meteorological observations made in Portugal are short and most of them from the period from 1770 to 1793. Prior to that, data on temperature, precipitation and air pressure were collected in Funchal, Madeira Island, between 1747 and 1753 by the English doctor Thomas Heberden. The earliest records concerning continental Portugal were made in Lamego (1770–1784) in northern Portugal. Measurements were carried out by J. Borges da Veiga who was a correspondent of the *Academy of Sciences*. Two German engineers, i.e., Jacob Praetorius and Heinrich Schulze came to Portugal as military officers to support the reorganisation of the Portuguese army and carried out diversified meteorological observations in Lisbon, between 1777 and 1783 and in 1789 (Taborda et al. 2004). Between 1783 and 1787 the physicist Joaquim Velho made very accurate daily observations in Mafra (near Lisbon) some of which were published by the *Academy of Sciences*; in 1792 the medicine doctor Bento Lopes carried out daily measurements in Oporto.

Most of these readings are reported in tables with meteorological observations. The data usually included qualitative annotations that supplemented numerical information. The meteorological instruments were often built by the academicians, with the help of information imported from other European Academies, and were described in detail in order to legitimate the data.

During the first half of 19th century the instrumental observations were carried out by Marino Miguel Franzini (1779–1861) a major of the Royal Corporation of the Engineers, Liberal deputy, Finance Minister and meteorologist. Two series of monthly data, not statistically different, were compiled during the 1815–1825 and 1836–1854 periods. The data from December 1815 to December 1817 were issued in the *Memórias* of the Portuguese *Academy of Sciences* while after 1818 data were published in the weekly and monthly press. Franzini's main station was located not far from the current Meteorological station in Lisbon and the microclimatic environment was not very different from today.

### 2.2 Spain

In Spain, Doctor Francisco Salva, following the protocol of the *Société Royale de Medicine*, Paris, began in 1780 the daily series of instrumental records in Barcelona (N-SP). Original logs are preserved at the Academy of Medicine of Barcelona. In 1884, the University of Barcelona took charge of the observations. Monthly series of precipitation are available since 1787 although with some gaps related to violent events during the first half of 19th Century, i.e., Napoleonic Wars and Civil Wars.

The series of Cádiz-Seville (S-SP) are two neighbouring towns in which the Spanish Navy headquarters, academies and observatories promoted cultural and scientific activities during the 18th century. In 1753, the Navy Academy (*Academia de Guardia-Marinas*) installed the first Royal Observatory in an old castle in Cadiz, and started meteorological observations. In 1797, a new Navy Observatory was built in San Fernando (6 km far from Cadiz) and the observations continued uninterruptedly till today. Logs are affected by frequent gaps, some caused by the Napoleonic Wars and some because of missing registers. In 1870 the Navy Observatory started to produce continuous and homogeneous series of the key weather variables at hourly resolution, including precipitation. In the period from 1820 to 1880 three brothers living in Cadiz generated another series of 3 observations a day (including pressure, temperature, wind direction, sky conditions) and daily precipitation as well, available from 1847 to 1880 (Barriendos et al. 2002).

### 2.3 Southern France

In Southern France, the earliest weather observations were recorded by the Royal Company excavating the *Canal du Midi* (i.e., the Canal crossing Southern France, called “Midi”). This canal was a waterway excavated in 1681 to link the Atlantic with the Mediterranean Sea. The Company was active between the end of the 17th century and the French Revolution in 1789.

Other observations used in this work were provided by some members of the *Académies des Sciences* of Montpellier and Toulouse, linked by law to the central *Académies des Sciences* in Paris. The most active observers in Montpellier were François Xavier Bon, Jean Baptiste Romieu and Jaques Poitevin who made readings in 1699–1754, 1758–1812 and 1767–1806, respectively. However, precipitation was regularly recorded only since 1770, starting with Romieu. He died in 1766 but his work was immediately resumed by Poitevin, who continued readings till 1806. After them, measurements were carried out by the Faculty of Sciences at the local university (Roche 1898).

The Jesuit order was active since 1740 and founded astronomical and weather observatories in Southern France, in Lyon, Marseille, Toulouse and Montpellier (Roche 1898; Delattre 1953; Udias 1996). The observations started with temperature and barometric pressure and later included precipitation, sky condition and barometric pressure. The Jesuit order was suppressed in 1773 and restored in 1814, causing a large gap in observations, and the situation worsened with the troubles provoked by the French Revolution till 1850’s.

The situation changed in 1860, when Urbain Le Verrier (Paris Observatory) and George Biddel Airy (Greenwich Observatory) established an international cooperation of weather networks to collect and share in real time meteorological observations to predict storms. This represented the start of the modern meteorological network and the inspiration for the creation of National Meteorological Services, e.g., Spain and Italy.

In this paper we used precipitation records from the Observatories of Toulouse, Lyon and Montpellier starting from 1770 because of their higher reliability (Garnier 2010). Many other earlier observations exist, but their acquisition, correction and homogenization require a long time and might be considered in the future.

### 2.4 Italy

The daily series of precipitation in **Padua and Bologna** (N-IT) were initiated in 1716 by Giovanni Battista Poleni and Jacopo Bartolomeo Beccari, respectively. Padua had a gap in 1719–1724. Both joined as corresponding members the Network of the *Royal Society* of London answering the invitation by Jurin (1723). Later, both series adhered to the *Societas Meteorologica Palatina*, Mannheim (1783–1795) following the invitation by Hemmer (1783). The series of monthly totals of the precipitation in Padua reported in the original logs at the end of each page was published years ago (Camuffo 1984). Now both series have been recovered at daily resolution from the original registers, have been carefully revised, corrected and homogenized. In addition to some corrections from metadata, a careful analysis has put into evidence some instrumental/observational errors responsible for a small under evaluation, e.g., in Padua for the period 1811–1871, that have been corrected. The history of both series has already been published, i.e., **Padua**: Camuffo (2002); **Bologna**: Baiada (1986) and Brunetti et al. (2001). In particular, the data from 1813 to 2000 that have been utilized in this study are reported by Brunetti et al. (2001). We recently recovered the earliest part of the Bologna series, i.e., 1716–1792, including temperature, pressure and precipitation, and we will present it in a future publication.

The daily series of precipitation in **Milan** (N-IT) was initiated by Father Giuseppe Luigi Lagrange in 1763, who installed a rain gauge on the terrace of the tower of the Brera Astronomic Observatory. Details about the long history of this series and the Observatory in general are reported in Maugeri et al. (2002) and Chlistovsky et al. (1999).

In the same period, in **Naples** (S-IT) regular observations were made by Niccolò Cirillo and his pupil Francesco Serao from 1716 to 1761 (Mecatti 1761), although with some gaps. Air temperature, pressure and winds directions, sampled only once a day, started in 1727. After a long gap, observations started again in 1821 at the Capodimonte Astronomical Specola with Carlo Brioschi (Alberti 1901 and Aurino 1935) and continued till now (Department of Earth Science, Naples University). The monthly precipitation series were corrected for different elevations of the rain gauges from ground, and the gap between 1782 and 1820 was filled with a regression analysis involving the series at the Collegio Romano, Rome.

**Benevento** (S-IT) has regular rain gauge observations from 1869 to 2007 (Diodato 2007). For the period 1869–1960 the series is composed from a number of stations on the east of the town, not more than 400 m far from the city centre, so that all of them are representative of the same locality.

**Locorotondo** (S-IT) has temperature and precipitation observations beginning from 1829 and the series is unbroken till today. However, in 1883 the observatory was relocated in a site at a higher level, and this induced a discontinuity. The first part 1829–1883, is published in the Italian Meteorological Annals (Millosevich 1882, 1884).

**Palermo** (S-IT) has two parallel daily series. The former was born in 1791 thanks to Giuseppe Piazzi, director of the Astronomical Observatory, and was located in the Royal Palace, 2 km from the shore. The latter, i.e., Valverde, was born in 1880 in the Meteorological Observatory, some 5 km inland. The observations of the Astronomical Observatory are considered more reliable thanks to their homogeneity (Chinnici et al. 2000). Although precipitation was recorded since 1795, no data are available before 1797. The first original rain gauge was badly located and "when rain was heavy, the gauge lost a lot of water" as commented in the log. For this reason it was relocated on the Observatory roof in 1805. It was substituted three times, in 1832, 1851 and 1951, and the last one, provided by the Civil Engineering Ministry, is still in use today. The readings have been published by Micela et al. (2001).

## 3 Data analysis and discussions

The daily readings were recovered from the original logs and corrected on the basis of the historical and metadata documentation of the logs themselves, observers' correspondence and related literature in order to obtain a series per each location. The selected series are of high quality; however, it should be considered that in general, the precipitation readings may by affected by an error ranging from 3 to 30 % less than the actual precipitation reaching the ground (WMO 1983) and in some cases it might reach ±40 % (Tuomenvirta 2001). The precipitation was expressed in terms of anomaly, i.e., the departure of the actual readings from the corresponding average in the 1961–1990 reference period. It was not convenient to express the departure in terms of difference, because in regions with scarce precipitation, e.g., Southern Iberia or Southern Italy, even small differences in precipitation may correspond to no rain at all, or twice or three times the usual amount. In order to avoid any misleading interpretation, precipitation departures have been expressed in terms of normalized ratios, i.e., percentages referred to the 1961–1990 period. In such units the figures are easily interpreted: 0 means no precipitation, 0.5 represents 50 % of the average precipitation in the reference period, 1.0 represents the coincidence with the reference period, 1.5 means 150 % of the above average etc. This methodology is similar to the representation followed by IPCC 2007 (Le Treut et al. 2007).

*Homogenisation* The next step consisted in statistical testing of the records, through a cross comparison between series belonging to the same climatic area using a number of tests. The first test was the well-known Standard Normal Homogeneity Test (SNHT) by Moberg and Alexandersson (1997a, b). The second test was the double-mass test (Searcy and Hardison 1960; Wigbout 1973; Buishand 1981) calculating year by year the cumulative values of a selected station versus the corresponding cumulative values of another station chosen for reference. The result is a straight line in case of fully homogeneous series, as opposed to an abrupt slope change of the graph line from the year of the discontinuity, if a change occurred in one of the two series. The third test was to subdivide the precipitation into classes of intensity (mm/month) and analyze if the frequency of any class had discontinuities over the time. This test revealed that an instrument used for a certain period had 0.5 mm threshold. The reason was some water stagnant at the bottom of the collector and this caused an underestimation of the readings.

The non-parametric **Mann-Kendall (MK) test** (Mann 1945; Kendall 1975) was applied to identify trends, if any, in time series. Online Resource 3 reports the results and the significant levels for the individual sub-areas and the whole Western Mediterranean Basin.

*From individual stations to regional precipitation series* Each region is composed of a number of stations located in a subarea with common geographic and climatic features. In the case a station had a short gap, or started a bit later, the missing data were reconstructed from some other neighbouring stations, in order to obtain averages from a number of series having all the same length. Missing data were reconstructed as a weighted average, the weight being determined by the ratio of the coefficient of determination $R^2$ between two selected neighbouring stations per each season. A problem was that, for some geographic and climatic features, the relationships ($R^2$) between stations had some seasonal variability. In order to account for this problem, the weights were seasonally updated, and the general equation was:

$$Y_{Missing\ data} = \frac{1}{\left(\frac{R^2_{Station\,1}}{R^2_{Station\,2}}\right)+1} * X_{Station\,1} + \left(\frac{\frac{R^2_{Station\,1}}{R^2_{Station\,2}}}{\left(\frac{R^2_{Station\,1}}{R^2_{Station\,2}}\right)+1}\right) * X_{Station\,2}$$

The case of Southern Italy is illustrated as an example of a complex situation where the mid-season and the winter precipitation regimes were partially mixed with variable seasonal contribution. Missing data in Naples have been obtained from Roma and Palermo; the same for Benevento and Locorotondo stations. Table 1 reports the coefficient of determination ($R^2$) used to obtain the weights in the equation for reconstruction of missed data.

When the area was not adequately covered, or the distribution of stations was not homogeneous, or the individual records had a too diverse length, the average was possible only for the common overlapping periods, although this caused to loose the earliest, unevenly documented period. For this reason, the averaged Western Mediterranean Series was constraint by the shortest of the contributing regional series, and begins in 1797, although the earliest regional series began in 1725.

**Table 1** Table reporting the coefficient of determination ($R^2$) between stations in Southern Italy used to reconstruct missing data as a weighted average from the neighbouring stations of Rome and Palermo

| Station | Winter ($R^2$) | Spring ($R^2$) | Summer ($R^2$) | Autumn ($R^2$) |
|---|---|---|---|---|
| Correlation between Naples and | | | | |
| Roma | 0.52 | 0.37 | 0.20 | 0.31 |
| Palermo | 0.05 | 0.16 | 0.03 | 0.06 |
| Correlation between Benevento and | | | | |
| Roma | 0.46 | 0.30 | 0.16 | 0.23 |
| Palermo | 0.06 | 0.13 | 0.09 | 0.05 |
| Correlation between Locorotondo and | | | | |
| Roma | 0.09 | 0.13 | 0.14 | 0.08 |
| Palermo | 0.21 | 0.16 | 0.13 | 0.16 |

*Comparison with Pauling's et al. mixed multiproxy and instrumental reconstruction* In order to pinpoint low frequency variability, the series have been associated with their filtered moving average, i.e., the 11 year running average as in IPCC 2007 (Le Trout et al. 2007). Per each station, the actual average (in mm) of the 1961–1990 reference period is reported in Table 2. In addition, each graph reports the running average of the reconstruction made with the Pauling's gridded dataset (Pauling et al. 2006) for the same location in order to verify how the Pauling's mixed multiproxy and instrumental reconstruction fits with the newly recovered instrumental observations, especially for the earliest period. The Pauling's et al. reconstruction for the 1500–1900 period was based on precipitation indexes (i.e., documentary evidence, tree ring chronologies, ice cores, coral and a speleothelm) and the 1901–2000 period on gridded reanalysis of long instrumental precipitation series. The Pauling et al. instrumental stations are mainly distributed over UK and Central Europe, less over the Mediterranean area.

### 3.1 Regional data analysis

**Lisbon, Portugal** (Fig. 1) is rainy in winter and dry in summer. For this reason summer peaks are mainly determined by the low value, i.e., 30 mm, of the 1961–1990 reference

**Table 2** Table reporting seasonal average precipitation (mm) for the individual sub-areas in the 1961–1990 reference period. In bold the season with maximum precipitation, in italic the season with minimum precipitation are reported

| Seasonal precipitation amount | Winter DJF (mm) | Spring MAM (mm) | Summer JJA (mm) | Autumn SON (mm) |
|---|---|---|---|---|
| Portugal (PT) | **314** | 164 | *30* | 206 |
| Northern Spain (N-SP) | 116 | 140 | *107* | **222** |
| Southern Spain (S-SP) | **251** | 121 | *19* | 187 |
| Southern France (FR) | *158* | 164 | 165 | **179** |
| Northern Italy (N-IT) | *180* | 229 | 219 | **234** |
| Southern Italy (S-IT) | **239** | 150 | *78* | **239** |
| Western Mediterranean | 189 | 161 | *118* | **212** |

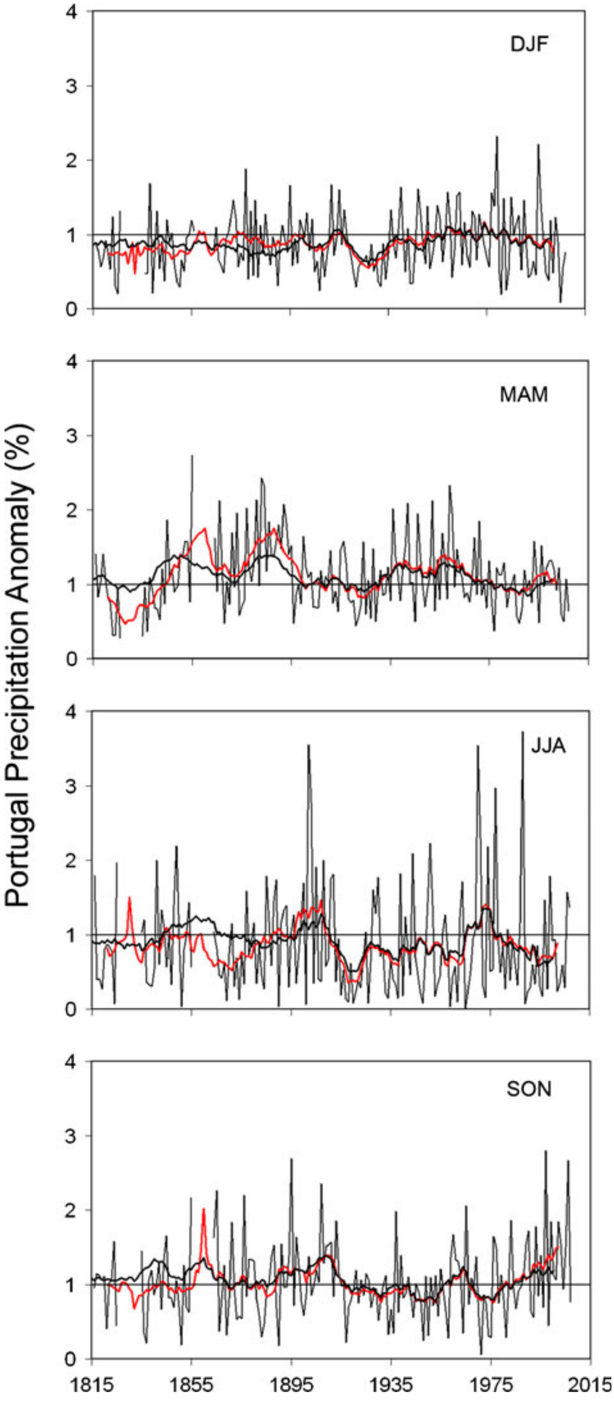


**Fig. 1** Normalized precipitation anomaly (%) per each season, reference period 1961–1990, Lisbon (PT). From the *top* to the *bottom*: Winter (DJF), spring (MAM), summer (JJA), autumn (SON). The *thick red line* is the 11 year running average, the *thick black line* is the 11-year running average of the reconstruction made with the Pauling's gridded dataset (Pauling et al. 2006) for the same location. The horizontal thin black line refers to the seasonal average precipitation in the 1961–90 reference period (see Table 2)

period that amplifies the anomaly in the case of a more abundant precipitation. The winter precipitation is almost regular, with increased extremes in the most recent decades. In the

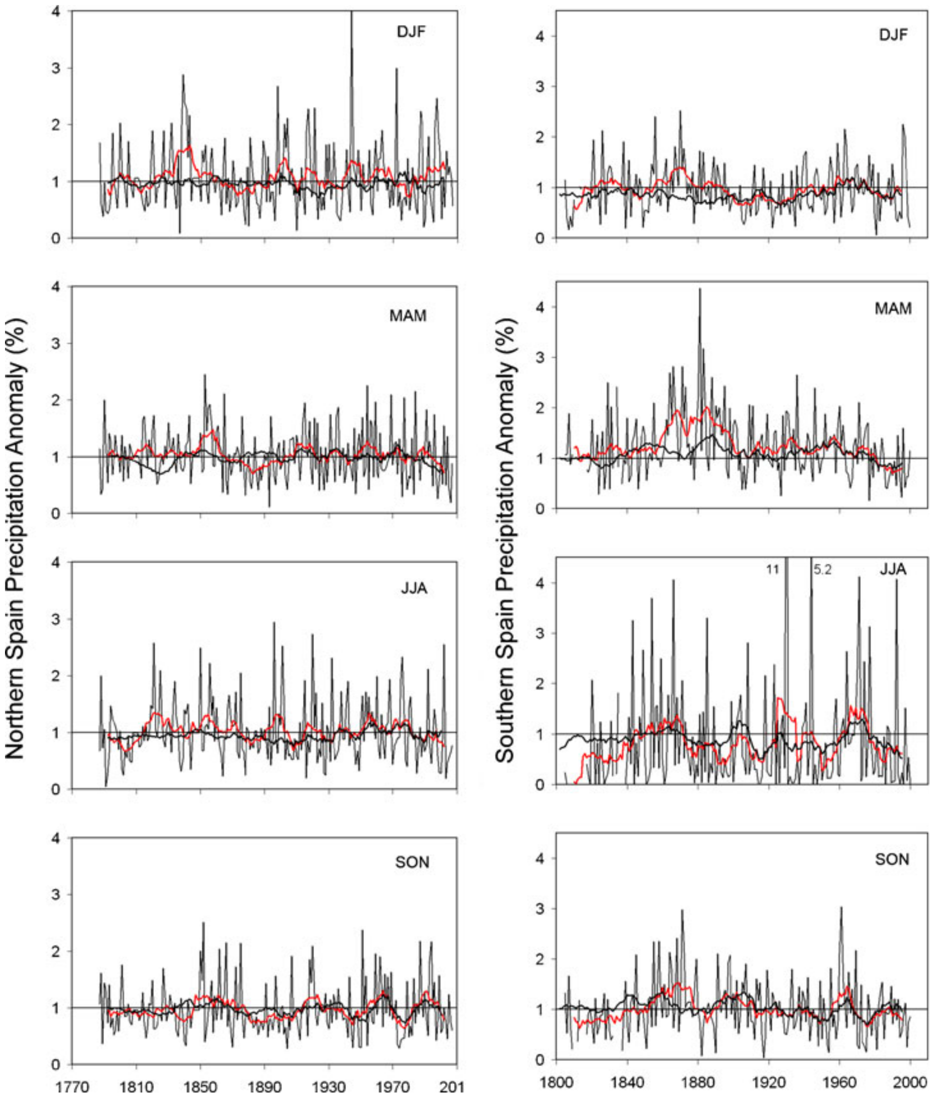
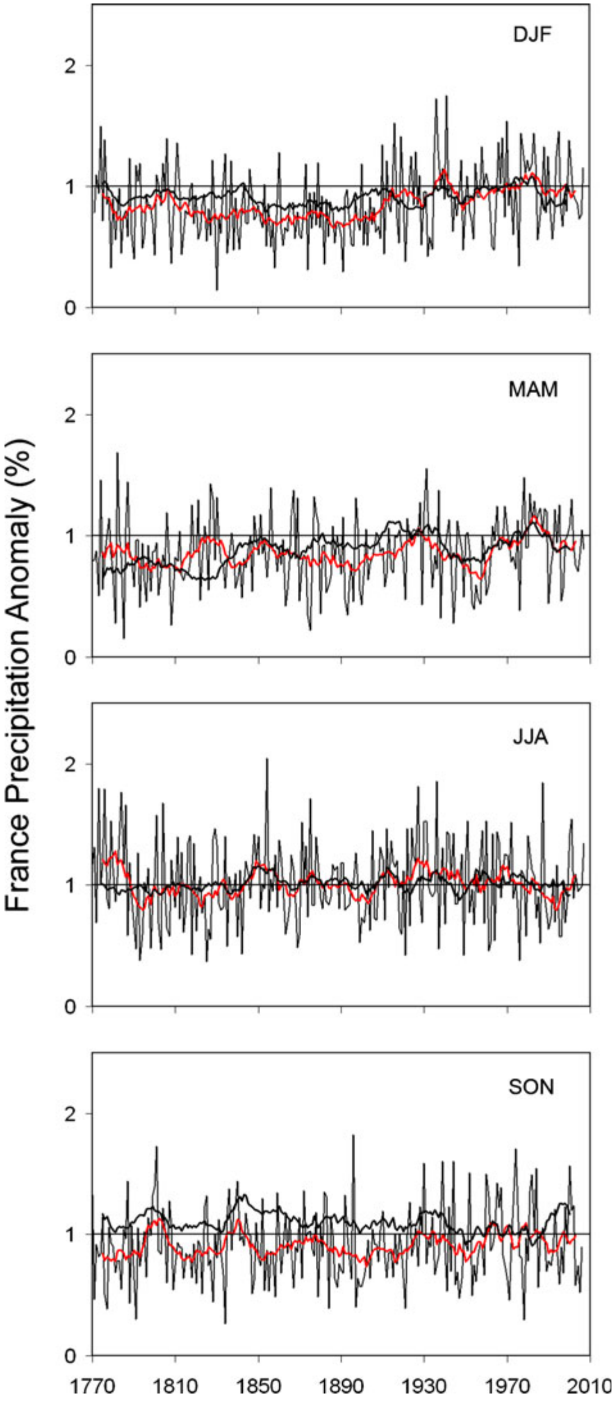


**Fig. 2** Normalized precipitation anomaly (%) per each season, reference period 1961–1990, for Spain. **a** Barcelona, Northern Spain (N-SP). **b** Cadiz-Seville, Southern Spain (S-SP). Symbols and reference as in Fig. 1

other seasons swings are visible but no significant trends have been found with the MK test. In the most recent decades, summer precipitation is slightly decreasing, and the autumn one has the opposite trend. Swings and no trends have been already noted by De Lima et al. (2010) and Tildes-Gomes (2005). A comparison with the Pauling et al. reconstruction shows good agreement after 1900; less in the previous period.

**Barcelona, Northern Spain** (Fig. 2a) Autumn is the most favourable season for precipitation, while summer is the less. Marked swings compared with Portugal and Cadiz-Seville. Large peak variability in winter, a peak exceeding 400 %. No trends are evident. The Pauling et al. precipitation is lower than the present study, except for the mid-seasons after 1900.

**Fig. 3** Normalized precipitation anomaly (%) per each season, reference period 1961–1990, Southern France (FR). Symbols and reference as in Fig. 1



**Cadiz-Seville, Southern Spain** (Fig. 2b). The rainy period is winter and summer is arid. In summer, the extreme events and swings are apparently made stronger for the low level of

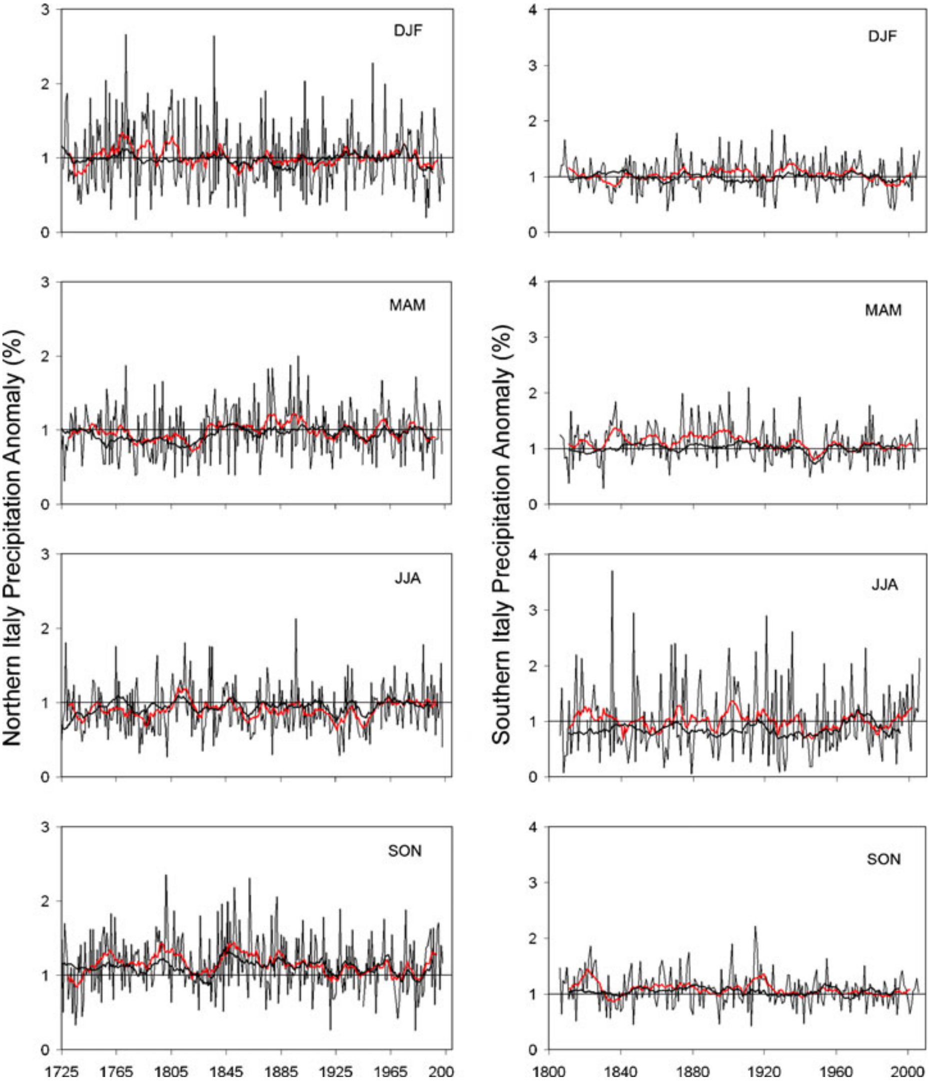


**Fig. 4** Normalized precipitation anomaly (%) per each season, reference period 1961–1990, for Italy. **a** Northern Italy (N-IT), **b** Southern Italy (S-IT). Symbols and reference as in Fig. 1

the normalization factor, i.e., 19 mm, and this partially holds for the mid seasons too. This might help to interpret the non-linear relationship between changes in mean and standard deviation observed by Rodrigo (2002). Winter and spring had larger swings in the 19th century in comparison with the 20th century; summer and autumn have regular swings over the whole period. Slight decreasing trend in spring (see MK test in Online Resource 3). No special features for the most recent decades. The Pauling et al. reconstruction is close to our results after 1920 and generally damps wings.

**Southern France** (Fig. 3) Precipitation is almost equally distributed over the calendar year, with a slight prevalence during summer and autumn. An increasing precipitation trend is visible in winter and spring (see MK test in Online Resource 3); swings around the average level. No particular trends over the most recent decades. A previous study concluded that, while major floods happened in this region, the various locations presented only minor changes in precipitation, and not in the same direction (Pujol et al. 2007). The Pauling et al. reconstruction generally provides more precipitation than our study.

**Northern Italy** (Fig. 4a) is the longest instrumental record, beginning in 1725. Autumn is the rainiest season, followed by spring, winter and summer, the precipitation regime being largely controlled by the passage of the Atlantic perturbations. Some swings are visible. A decreasing trend in autumn (see MK test in Online Resource 3). In the most recent decades autumn is wetter, the other seasons almost unchanged. Generally good agreement with the Pauling et al. reconstruction but with some larger departures in the 18th century.

**Southern Italy** (Fig. 4b). The precipitation regime is typically Mediterranean, with the maximum in autumn and winter, with dry summer (78 mm). Summer is characterized by frequent precipitation peaks amplified by the relatively small normalization factor. A decreasing trend in spring (see MK test in Online Resource 3). The Pauling et al. reconstruction is lower than our observed data from the beginning to 1920, especially for spring and summer precipitation.

### 3.2 Principal Component Analysis

The geographical extension of abundant precipitation or aridity and the spatial relationship between the stations was analysed using the Principal Component Analysis (PCA). PCA is a bilinear modelling method that provides an interpretable overview of the main information contained in a multidimensional set of data, i.e., the precipitation anomalies, and transforms them onto a smaller number of latent variables called Principal Components (PC). In a two-dimensional scatter plot having the first two PC, i.e., PC1 and PC2, as main axes, each precipitation anomaly series is represented by a vector and the relationships between the series is determined by their position in the plot, and the angle between them. Stations forming an acute angle are correlated between them, while the ones forming 90° are uncorrelated and at 180° have opposite correlation. The inner ellipse indicates 50 % of the explained variance and the outer 100 %, and we should focus the attention to the vectors falling in the belt between the two ellipses. Stations close to the centre do not contain enough variance to be discriminated and cannot be interpreted.

All anomaly series except Portugal have been considered for their common period, i.e., since 1797. Portugal has been excluded because it was shorter and would have penalized this analysis. From the analysis of Online Resource 4 we observe that in winter (Online Resource 4a), Northern Italy is almost coincident with Southern Spain and Northern Spain is almost uncorrelated with the above two geographical areas. Other connections are less representative (i.e., less than 50 % variance) because fall within the smaller ellipse. In spring and autumn Northern Spain and Southern Spain are again almost independent from each other. In summer (Online Resource 4c), Southern Italy and Southern Spain are almost independent from each other.

### 3.3 The Pearson coefficient

The Pearson coefficient R was obtained by matching each individual precipitation series with all the others in various localities, season by season (Online Resource 5). In winter, Northern Italy is highly correlated with Cadiz-Seville and Southern Italy. In spring, poor correlation are visible. In summer Northern Italy is highly correlated with Barcelona (N-SP) and similarly with Southern Italy. Autumn is characterized by no significant correlations.

The PCA analysis and the findings with the Pearson coefficient generally correspond; there are only slight differences due to the fact that the first two components PC1 and PC2 of the PCA analysis take into consideration only 60–70 % of the total information, depending on the season. The remaining information is explained by the further PC, not reported here because less relevant.

### 3.4 The harmonic analysis

The harmonic analysis, made with the Wavelet Power Spectrum applied to all the sub-areas for the four seasons shown only a few cases with significant cycles at 95 % confidence level (CL). France in spring has an apparently significant peak at 80 year, but close to the limiting cutoff frequency compatible with the sampling theory and aliasing. Northern and Southern Italy in autumn have a significant peak at 48 year that persisted from the origin up to 1880 (Online Resource 6). No other significant periodicities have been found. Piervitali and Colacino (2001), analysing the proxy series of ceremonies in case of draughts in Sicily from 1565 to 2000, noted periods of 11, 17, 22, 32, 73, and 90 year, not coincident with our results.

### 3.5 Analysis of the Western Mediterranean Basin

A Western Mediterranean series has been obtained by combining all of the above series limitedly to their common period, i.e., beginning from 1797 (Fig. 5). The combination of the stations over a wide area has attenuated the variability of the signal and no trends are visible over the whole period (see Online Resource 3). In the most recent decades no special features are evident except for a magnification of the last swings. The comparison with the Pauling et al. reconstruction is generally in good agreement over the whole period, except for spring where Pauling et al. is lower than the observed data.

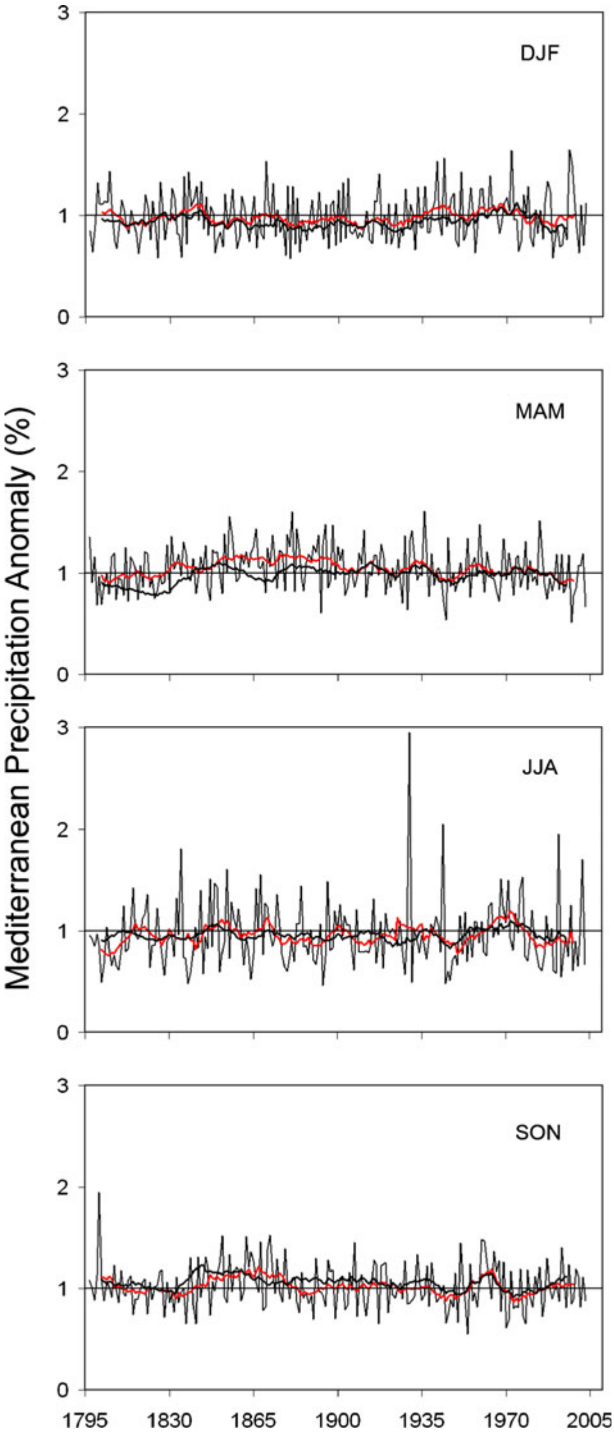
A test was made to see how the cumulative precipitation departure from the 1961–1990 reference period progressed over the time (Online Resource 7). In this test, a line parallel to the horizontal axis indicates a period with unchanged precipitation, with seasonal amount equal to the reference period; if the precipitation is lower than the reference period, the line is decreasing; if increasing, greater. In winter precipitation was close to the reference period from 1797 to 1850 and from 1935 to 2000; less than the reference period from 1851 to 1934. Spring precipitation was more abundant till 1899; similar to the reference after 1900. Summer is generally less than the reference period, but with swings. The general trend of summer precipitation is similar to winter except after 1935. Autumn precipitation was heavier from 1840 to 1880, then equal to the reference period. The Pauling et al. reconstruction in general shows the same qualitative tendencies, but lower winter and especially spring precipitation over the 19th century; summer is closely represented; autumn is higher from 1840 to 1920.

The Wavelet Power Spectrum applied to the Western Mediterranean shows only one cycle at 95 % confidence level (CL) at 56 year in autumn (Online Resource 8)

## 4 Conclusions

The earliest regular instrumental observations of precipitation date back to early 18th century in Northern Italy; late 18th century in Spain, Southern France and Southern Italy; mid 19th century in Portugal. The exceptional length of daily instrumental observations series of

**Fig. 5** Normalized precipitation anomaly (%) per each season, reference period 1961–1990, for the Western Mediterranean Series. Symbols and reference as in Fig. 1



proved quality makes the results of this study particularly significant for the combination of long time and wide space scales, which reduce the influence of local effects. In particular, this study extends back to one century our knowledge about the instrumental precipitation readings over the Western Mediterranean, and to two centuries in some specific subareas. This provides a unique opportunity to calibrate models for the period before 1900.

In the regional series considered in this study, only a few modest trends with opposite tendencies were found over the whole period. In winter the trend was increasing in Southern France; in spring it was decreasing in Southern Spain and Southern Italy and increasing in Southern France; in summer no trends; in autumn decreasing in Northern Italy. The Western Mediterranean series had no significant trends.

The regional series in the most recent decades don't show any homogeneous tendency: some of them remain almost unchanged, some tend toward dryness and some toward increasing rain.

All the regional series and the Western Mediterranean series are characterized by repeated swings between rainy and dry periods, as already noted by Piervitali and Colacino (2001); Xoplaki et al. (2004); Tildes-Gomes (2005); De Lima et al. (2010) and IPCC 2007 (Le Treut et al. 2007).

The reconstruction made by Pauling et al. (2006) is in general good agreement with the observed data especially after 1900; in the previous period some departures have been noted, either with lower or higher reconstruction compared with the present study. This is justified because Pauling et al. used proxies from the beginning of the series to 1900 and the reconstruction is subject to the intrinsic uncertainties of proxies; the subsequent 1901–2000 period, based on instrumental observations is in close agreement with the long instrumental series produced with this study.

The multi-decadal oscillations in the Mediterranean precipitation have a significant 56 year cycle for the autumn precipitation only. This cycle corresponds to the circa 54–56 year Saros Cycle of eclipses caused by the positions of the Sun and the Moon, known since the Egyptian and Babylonian times. This cycle might be purely coincidental. However, it is well known (e.g., UK Meteorological Office 1962; Reiter 1975) that the Mediterranean precipitation in spring and autumn is generated by Atlantic perturbations entering the Mediterranean and it is governed by the difference between air and sea surface temperature (SST). The SST over the North Atlantic is affected by multidecadal variability, in particular 56 year cycle (Delworth and Mann 2000) that reflects on the Mediterranean precipitation. In spring this cycle is masked by the larger circulation variability. In summer the Mediterranean precipitation is scarce, in winter abundant but both are not related to the Atlantic penetration. A 56 year cycle means that in the case of datasets not much longer than 60 year, the contribution of the last part of the ongoing oscillation might induce to misinterpret the plot in terms of decreasing trend. Long-term swinging is typical for the Mediterranean air as well as for waters and decadal oscillations have been observed in the Mediterranean Sea (Lionello et al. 2006; Pisacane et al. 2006) and are responsible for feedback with the local weather.

In the Mediterranean area, air temperature too is swinging although with some return periods, i.e., 57.3, 34.4, 26.5 and 2.2 year (Camuffo et al. 2010a, b) of which the first one, i.e., 57.3 year, is close to the autumn precipitation cycle, i.e., 56 year. Over the course of centuries, the combination of the temperature and precipitation cycles with different return periods caused an alternation of cold-humid, cold-dry, warm-humid and warm-dry similar to the present situation.

**Acknowledgments** For this long study, we are grateful to: the EU projects MILLENNIUM (Contract 017008-2) and CLIMATE FOR CULTURE (Contract GA 226973); the French projects OPHELIE and RENASEC; the ESF grant "Mediterranean Climate Variability and Predictability". For data and/or discussions we are grateful to the following colleagues: M. Fragoso, Lisbon University: T. Nanni, and M. Brunetti, CNR-ISAC, Bologna; GP. Maracchi and A. Crisci, CNR-IBIMET, Florence; M. Sulli, Istituto Sperimentale Selvicoltura, Florence; G. Micela, V. Iuliano and D. Randazzo, Astronomical Observatory "Vaiana", Palermo; L. Buffoni, F. Chlistovsky and M. Maugeri, Milan University; V. Zanini and L. Pigatto; University Library, Padua; L. Prosdocimi, Library of the Astronomy Department, Bologna University; R. Stasi, P. Pirolo and S. Pelle, National Central Library, Florence; P. Galluzzi, A. Lenzi, G. Strano, A. Saviori; Museo Galileo Institute and of History of Science, Florence; Father P.D. Spotorno, Library of the Vallombrosa Abbey; E. Borchi and R. Macii. Ximenes Observatory, Florence.

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