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Climate Change in the Mediterranean over the Last Five Hundred Years

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1. Introduction

Global Warming (GW) is expected to affect the Mediterranean area with three major challenges, i.e. increase in temperature, decrease in precipitation and sea level rise that will likely submerge the coastal areas, including Venice. Aim of this Chapter is to discuss the expected changes under the light of long-term observations. Documentary proxies and instrumental readings in Portugal, Spain, France and Italy have been recovered and analysed. These observations cover the last five centuries from the Little Ice Age (LIA) to the present-day GW.

This Chapter is based on documentary proxies and instrumental series collected over the Mediterranean area, i.e. Portugal, Spain, France and Italy (Fig.1) within the EU funded ADVICE, IMPROVE, MILLENNIUM, and Climate for Culture projects. A huge effort was made to seek for written sources and original logs with early and less recent instrumental readings. The next steps were to recover, correct, adjust to modern standards, homogenize and analyse the earliest data and most of the longest European series. The detailed study of the history of the series (e.g. instrument type, calibration, observational methodology, sampling time, exposure, location) and the recovery of any related metadata were fundamental to apply and perform the due corrections to the series. The methodology was presented in previous papers (Camuffo and Jones, 2002, Camuffo et al. 2010a)

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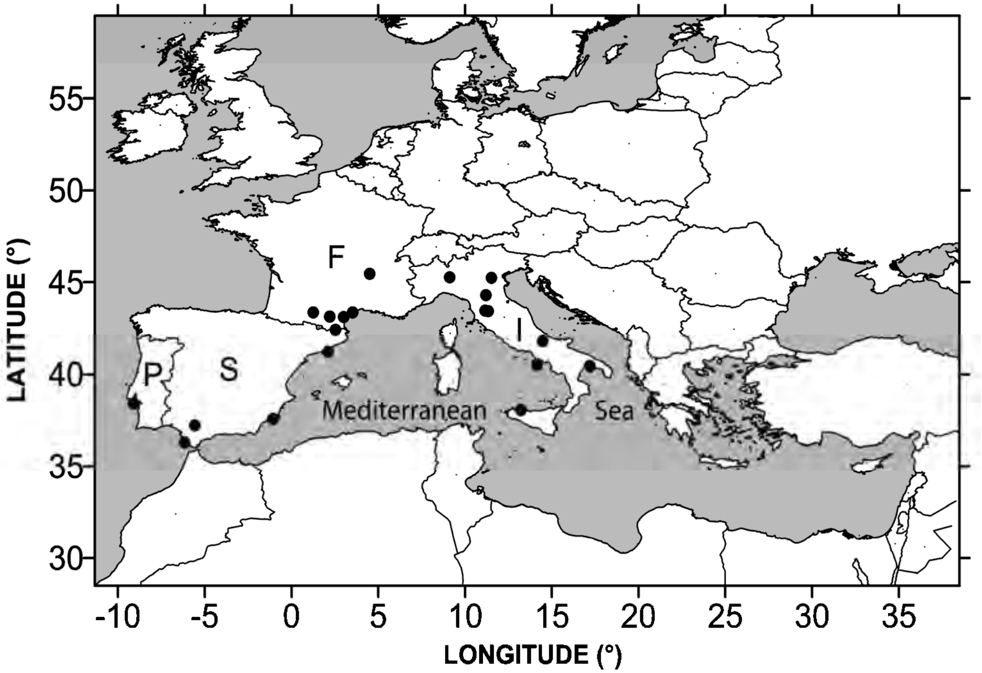

Fig. 1. The Mediterranean Basin with the indicated locations (black circles) where documentary proxies and/or instrumental observations have been retrieved for use in this Chapter, divided by countries, i.e.: Portugal (P), Spain (S), France (F) and Italy (I). The stations are: Lisbon (P), Cadiz (S), Seville (S), Murcia (S), Barcelona (S), Perpignan (F), Narbonne (F), Carcassonne (F), Toulouse (F), Montpellier (F), Lyon (F), Milan (I), Padua (I), Bologna (I), Vallombrosa (I), Florence (I), Benevento (I), Naples (I), Locorotondo (I) and Palermo (I).

2. Weather in the Mediterranean

The Northern part of the Mediterranean Basin is under the influence of the European continental climate, the shield of extended mountain chains and the penetration of external air masses through the mountain gates. The rest of the Basin is strongly conditioned by the difference in temperature between the air and the seawaters and the expected increase in temperature could reduce the annual precipitation, increasing the aridity in the warmest areas.

In the warm season (May-October) the Azores High is well developed and prevents external air from entering the Mediterranean. The local air is warmer than the seawater and blows over the Mediterranean with reduced heat and moisture exchanges, forming thermal layering, atmospheric stability and clear sky. In the warm season, precipitation is possible only on the Northern side, for the passage of Atlantic disturbances or the formation of convective clouds and afternoon thunderstorms especially in the mountain areas.

In the mid seasons, when the Azores High weakens, Atlantic disturbances penetrate and diagonally cross the Mediterranean, bringing cold air and stormy weather. The southern part of the Basin remains untouched, with no precipitation.

In the cold season, when continental Europe is cold, a high-pressure ridge forms over Europe, joining the Russian with the Azores High, and tends to block the passage of fronts and disturbances coming from West. Polar or arctic air blows from North or from East. During their motion towards lower latitudes, the cold air masses increase in temperature and depart more and more from saturation, so that no precipitation is possible on the Northern coast. However, when cold air blows over the Mediterranean Sea, the air gains heat and moisture from the warm water, forming atmospheric mixing, large clouds and precipitation on the downwind regions. Warm water feeds clouds and enhances depressions and storms, especially in the occasion of cold air inflows from North or East. The mountain chains surrounding the Mediterranean shield most of the basin but leave some open gates through which external air may enter with violence, determining some local strong winds e.g. Mistral, Libeccio, Bora, Etesians, Vardar and Sirocco. However, the worst stormy weather is associated with the penetration of low pressures from North or West. When a northern trough enters the Mediterranean in the cold season, it is fed by the warm water and generates violent storms on the Eastern coast of the Spain, Southern France and Italy. Atlantic depressions enter the Mediterranean crossing diagonally France and penetrating through the gate between the Pyrenees and the Alps, or crossing the Iberian Peninsula with a westerly circulation. Westerly depressions bring heavy precipitation over Portugal and Spain with decreasing intensity while advancing. When they enter the Mediterranean, they are fed by the warm seawater, increase in strength and cause heavy precipitation on the Eastern coast of Spain, Southern France and Northern-Central Italy. More details about the particularities of the Mediterranean climate can be found for instance in UK Meteorological Office (1962); Reiter (1975); Wallén (1970; 1977), Jeftic et al. (1992), Bolle (2003), Xoplaki et al. (2003; 2004); Fletcher et al. (2005), Lionello et al. (2006) Camuffo et al. (2010a,b), Glaser et al. (2010), Luterbacher et al. (2010).

3. Documentary proxies

3.1 Documentary sources in the Mediterranean area

In the period before the instrumental observations, the climate in the Mediterranean area is known after written sources that fully cover the Medieval Optimum and the LIA. This area is rich in documents concerning descriptions of exceptional or regular weather events and natural hazards, e.g. intense rain and rivers in flood; aridity, famine and rivers in low; severe cold killing people, animals and trees; freezing over large water bodies; regular weather and abundant yield. These documents may be manuscript or printed press and can be classified according their character and purposes, as follows.

- Narrative sources: generic descriptions of events, such as chronicles, annals, diaries, correspondence, poems and compilations of remarkable events written for historical purposes, the pleasure of informing or disseminating news.
- Ecclesiastic sources: registers noting liturgical services and rogation ceremonies commissioned by the local community or authority in the case of adverse conditions. The most relevant topics were: to beg for rain (pro pluvia) in view of the yield, or to

stop precipitation (pro serenitate) especially in the case of rivers in flood, or in the occasion of famine, plague, locust invasions or any other challenge.

- Administrative sources: official documents (e.g. diplomatic letters, municipal registers, inspection reports) written by public officers to describe some local catastrophe happened, its impact on the society and the landscape and the remedy actions to undertake, e.g. repair and maintenance, temporary reduction of taxes.

In principle, the most accurate sources are the Administrative ones, being written with the purpose of being absolutely precise and objective; then the Ecclesiastic ones reflecting the duration and severity of the extreme meteorological events, because the clergy followed a rather standardized style combining some liturgical formats with challenge severity level, being more solemn and complex with increasing hazard severity and risk. Abundant literature exists on the above subjects (Camuffo and Enzi, 1992a,b, 1994, 1996, 2010a; Enzi and Camuffo, 1995; Martín-Vide & Barriendos, 1995; Brazdil, 1999; Barriendos, 1997, 2005; Pfister et al., 1999; Alcoforado et al., 2000; Piervitali & Colacino, 2001; Barriendos & Llasat, 2003; Chuine et al., 2004; Brazdil et al., 2005, 2010; Luterbacher et al., 2006; Dominguez-Castro et al., 2008; Rodrigo & Barriendos, 2008). Written documents describe events with emphasis proportional to the impact that the event had on the society, the landscape or something else that the observer considered highly relevant to his advice. A number of severe events, confirmed by a number of dramatic consequences, were caused by some relatively short-term peaks, or drops, in temperature, precipitation or other meteorological variables. For instance, severe floods were generated by rain persisting over a limited number of days. The greatest winters in the history were renamed for some dramatic and spectacular effects (e.g. large water bodies unusually frozen over and supporting people) but were caused by two, three, maximum four weeks of very intense cold. However, from the comparison between documentary sources and instrumental observations, we see that such peaks and drops appear evident on the daily series, but tend to disappear when increasing the averaging period, i.e. they are almost damped on monthly averages. Therefore, some extreme events that are well known after written sources, when compared with instrumental data, may appear fully or partially justified depending on the temporal window used for the statistical analysis of the instrumental observations. Documentary sources are useful to establish the occurrence, and the frequency, of extreme events, the short-term variability, the persistence of some dry or wet, cold or hot periods particularly relevant to the agriculture, the landscape or the society. However, they are unable to provide long-term trends.

3.2 From written documents to indexes, and from indexes to proxy data

It is obvious that the written documents are extremely relevant because they qualitatively inform us about the weather and the climate in the period before the instrumental observations. Their value is even greater if they can be transformed from literary items into numbers to be used instead of instrumental readings. If such a case, the above written sources are transformed into “proxy data” that constitute an indirect way of assessing what historical temperature or precipitation might have been. Literally, “proxy” is a person having power of attorney, i.e. authorized to act for, or to represent another person on a single occasion. In the case some items are objectively related to temperature or precipitation, they can be considered “proxies”, i.e. a valid replacement of real instrumental observations if the latter are missing. If we can express proxies in numerical terms, and if we can in some way control and validate the numbers that we will obtain after having applied some transformation, we will obtain sound “proxy data” that will provide the needed information about past climate.

Written sources are transformed into proxy data following a careful series of transformations. First the sentence is interpreted, analysed and classified in terms of exceptionality looking at the description of the event and on the ground of objective facts, e.g. the effects it has produced. The classification is made attributing levels from +3 to a really extreme and well-documented event (e.g. extremely high temperature or abundant precipitation), as we can expect to occur not more than two or three times per century, to -3 to the symmetrical, but negative case (e.g. extreme cold or aridity). Levels ±2 and ±1 are used for intermediate levels at decreasing severity and of course level 0 is “normality”. The various severity levels are inspired to the departure of readings from the average, expressed in terms of standard deviation (SD), e.g. level 0 lies between ± 0.5 SD; levels ±1 lie externally to level 0 but are topped by +1 SD; and similarly with levels +2 topped by +2 SD; the levels ±3 being external to ±2 SD. In this way the episodes taken from written sources are indexed into severity levels, but they are not yet expressed in quantitative terms of degrees of temperature (°C) or precipitation amount (mm, or % in comparison with the precipitation occurred in a selected reference period). The transformation of an index into numerical values of temperature or precipitation, i.e. into a proxy data, is made with the help of a common period in which we have both such indexes and instrumental observations. In such a case it is immediate to find a correspondence between the two and know the transformation.

Proxies are useful in the absence of instrumental observations and their transformation is made in an objective way. However, they have some weak points, as follows:

- In some periods the documentation is scarce and we cannot be sure that the totality of the events, or what part of them, has been represented. In these periods it is impossible to know if the 0 level is “normality” or missing value.
- It is obvious that all the data are expressed in relative terms, the absolute reference level being missed. The transformed data are similar to the so called “anomaly”, i.e. the difference between the selected level and the 1961-1990 reference period for temperature, and the ratio between these two values for precipitation, but reference is made with the personal experience of the writer and not with a standard period.
- The severity is based on the witness of people living at that time, and reflects what was considered regular or extraordinary at that time. This means that the zero level, i.e. the “normality” remains flat: we can evaluate high-frequency fluctuations, but we miss long-term trends or cycles.
- Calibration and validation are based on a relatively recent period when simultaneous instrumental observations were available. However, going back in the time, we automatically extend the results to earlier periods in which the perception of man was different and conditioned by the culture of his time. This means that the calibration becomes uncertain when we extend it back over the previous centuries.

However, despite the above limits, proxy data constitute a very valuable source of information for the climate of the past centuries. The data analysis has been performed as already discussed in Camuffo et al. (2010a).

3.3 Results from the documentary proxies

This research was able to recover a satisfactory amount of proxies, sufficient to provide a reasonable documentation for all the four seasons in Northern-Central Italy followed by Southern France for temperature, and in Spain, Southern France and Northern-Central Italy for precipitation. The period after 1700 is better documented by instrumental records, but it has been useful for the calibration and validation of the proxies.

The temperature in Southern France is shown in Fig.2 and in Northern-Central Italy in Fig.3. In general, temperature is best documented in winter, followed by spring, for many complaints concerning cold severity, snow and frost. The less documented season is autumn, because in this season temperature is not a critical factor. In the period from 1500 to 1700, winter and spring seem having been characterized by cold episodes more frequently than today both in Southern France and in Northern-Central Italy. Hot summers have been more frequent than fresh summers, at least in Italy.

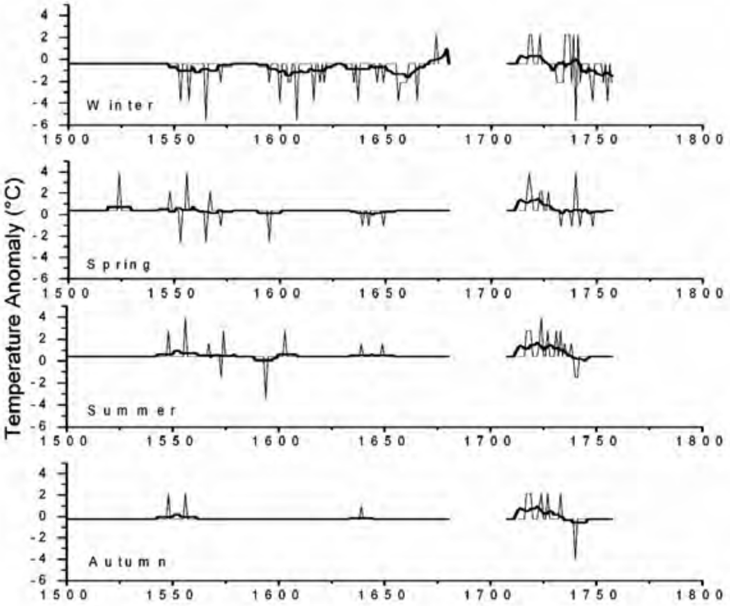

Fig. 2. Seasonal temperature anomaly (°C) from documentary proxy data in Southern France. The baseline has been set to be correspondent to the average of the whole instrumental period. Thin lines refer to proxies, thick lines to 11-year running averages. Seasons in the plots are related to DJF (Winter), MAM (Spring), JJA (Summer) and SON (Autumn).

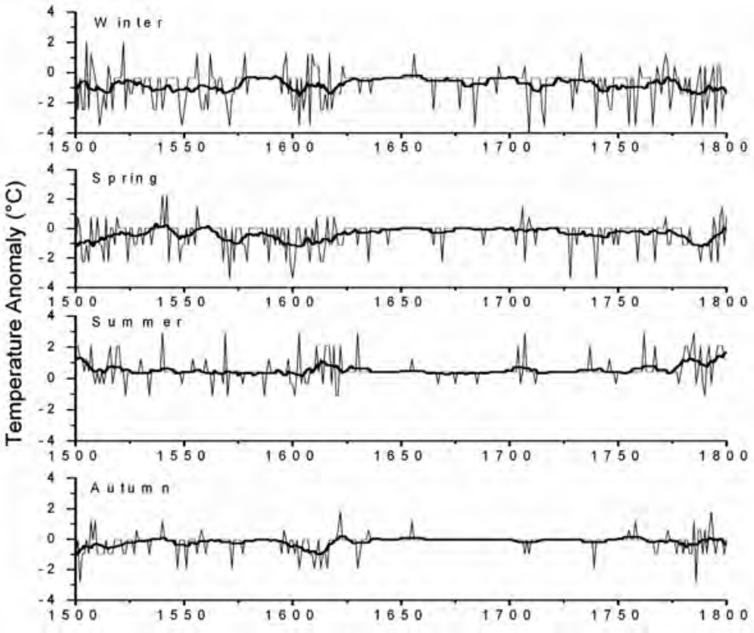

Fig. 3. Seasonal temperature anomaly (°C) from documentary proxy data in Northern-Central Italy. Symbols as in Figure 2.

The precipitation too is presented in terms of anomaly, but expressed as normalized ratio, i.e. the ratio between the observed values and the related ones in the 1961-1990 reference period, i.e. 0 means no precipitation, 1 the same precipitation as in the reference period, 2 is twice the precipitation observed in the reference, etc. This style follows IPCC 2007 (Le Treut et al., 2007).

The information concerning precipitation is more abundant in Spain (Fig.4) because this area is dryer than Southern France and Northern-Central Italy, with the consequence that people made frequent rogations and ceremonies to implore rain for crops. When rain occurs, it is intense or long lasting, and rivers risk being in flood. The risk of spot floods easily brings the local inhabitants to pray to stop rain. Documents are almost equally distributed over the four seasons, and in all of them ultra-decadal swings between dryer and wetter are visible. In Southern France (Fig.5) the precipitation is a less critical factor and for this reason proxies are less frequent. Rainfall is better documented in spring and summer because in these seasons rainfall is necessary for the growth and maturation of the agricultural products. In the second half of the 1500s and in the first half of the 1700s when the information density is higher, we can recognize two oscillations. In particular the 1550-1570 period rainfall was particularly abundant in summer and autumn.

In Northern-Central Italy (Fig.6) the information is quite regularly distributed along the whole period and among all the seasons. The most severe impacts of rain and dryness were from 1500 to 1620, with particular relevance in the two decades 1600-1620. Moderate swings of the 11-yr running average are visible.

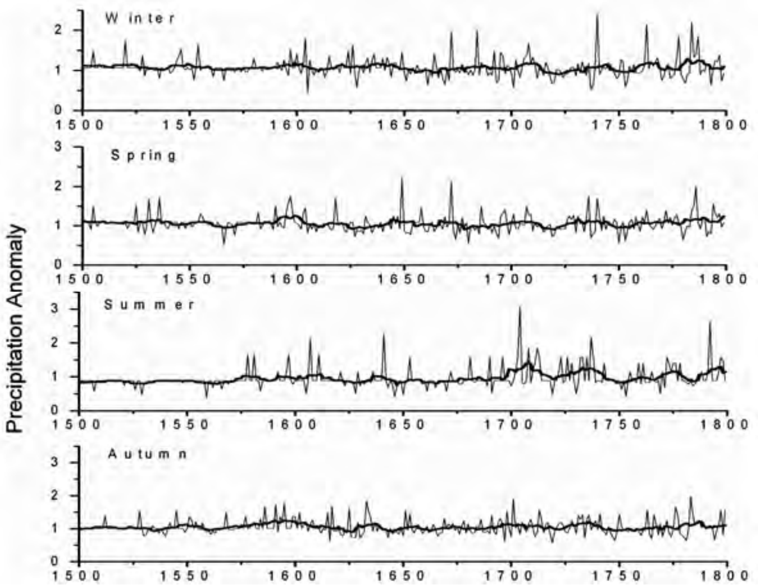

Fig. 4. Seasonal precipitation anomaly from documentary proxy data in Spain. Symbols as in Figure 2.

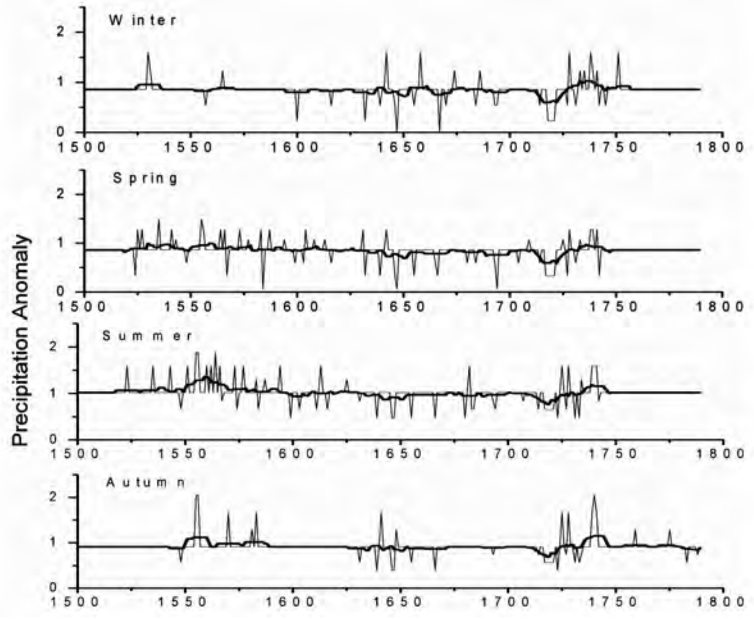

Fig. 5. Seasonal precipitation anomaly from documentary proxy data in Southern France. Symbols as in Figure 2.

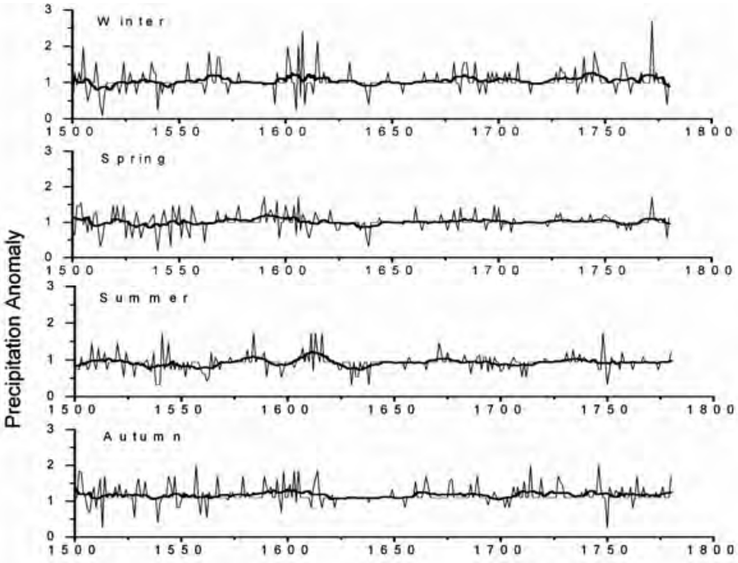

Fig. 6. Seasonal precipitation anomaly from documentary proxy data in Northern-Central Italy. Symbols as in Figure 2.

4. Instrumental series

The last period of the LIA and the present-day GW are well documented by the longest instrumental series that cover three centuries.

4.1 The earliest series of instrumental observations

The spirit-in-glass thermometer, the barometer, the rain gauge and some hygrometers were invented in Florence, Italy in the first half of the 17th century, where science flourished with Galileo, his pupils and the Grand Duke of Tuscany, Ferdinand 2nd De' Medici (Magalotti, 1666, Targioni Tozzetti, 1780) who was a supporter of the scientific research. He founded the first "modern" scientific Academy, i.e. the "*Accademia del Cimento*" (i.e. Academy of Experiment, flourished 1657 - 1667) with the first aim of investigating the Nature with particular reference to Mathematics, Physics, Astronomy, Meteorology, Biology and Medicine with instrumental observations and the second aim of expressing these disciplines in numbers and formulae.

In this context the Grand Duke organized the first meteorological network, called *Rete Medicea* (i.e. Medici Network), active for the 1654-1670 period with regular temperature readings taken 6 to 8 times a day in a number of stations. Unbroken series were Florence and Vallombrosa on the mountain slope near to Florence. All stations received from the Grand Duke thermometers with the same calibration and an operational protocol for the exposure in order to obtain strictly comparable readings. The thermometers used in the Medici Network are known as the Little Florentine Thermometer, entirely made of glass except for the spirit, and resistant to any kind of weather. The readings taken by this Network are the earliest regular observations in the world, and are of excellent quality (Camuffo, 2002; Camuffo et al., 2010°, Camuffo and Bertolin, 2011). The activity of the Medici Network was stopped by the Inquisition that hardly accepted the idea that somebody wanted to know the Nature from sources and modalities other than the Holy Bible.

Next century, James Jurin coordinated the next international network, with climate and health purposes, on behalf of the *Royal Society*, London. Unfortunately, Jurin (1723) suggested indoor readings for two reasons: people lived in unhealthy houses and most of the early thermometers, made with a glass capillary fixed to a wooden tablet with a iron wire were unable to resist to outdoors because the wooden shrinkage and swelling varied the iron wire tension, breaking the glass tube. Fortunately, some Italian observers made parallel observations indoors and outdoors following the local tradition. The Network was active from 1724 to 1735.

Some fifty years later, Vicq d' Azyr and Father Louis Cotte coordinated the next international network, also with climate and health purposes, on behalf of the *Royal Society of Medicine*, Paris. The Society published the meteorological observations from 1777 to 1786.

In the same period, the German Prince Karl Theodor von Pfalz launched another international Network, i.e. the *Societas Meteorologica Palatina*, Mannheim, with secretary Jacob Hammer (1783) who published readings in the "*Ephemerides Societatis Meteorologicae Palatinae*" from 1781 to 1792. This Network was of excellent quality with a precise sampling (i.e. three readings a day) and exposition protocol, and distribution of instruments to the observers who needed them. The thermometers were weatherproof, so that outdoor measurements were possible without problems.

The above meteorological networks had the primary merit of raising the public interest to regular daily observations, made with standardised instruments. All observers operated in the same way, with readings performed at the same sampling times and all instruments had similar exposure.

In the next century the meteorology was better developed, with several national and international initiatives, so that the number of available data was largely increased. The first most important milestone of the nineteen century was the creation of the national weather services around 1860, with the production of many high-quality series of regular instrumental observations made with standardized features. The second milestone was the foundation in 1873 of the *International Meteorological Committee* that in 1950 was transformed into the *World Meteorological Organization*.

4.2 Results from the instrumental observations of temperature

In this Chapter the temperature is presented in terms of anomaly, expressed as the difference between the observed values and the related values in the 1961-1990 reference period, following the IPCC 2007 style (Le Treut et al., 2007).

If we compare the instrumental records with the above documentary proxies, the first remarkable difference with the documentary proxies is the high time resolution and the high density of readings. All the plots show high-frequency fluctuations and ultradecadal swings, i.e. 12.7, 26.5, 34.4 and 57.3 yr over the whole set of data, that are characteristic of the Mediterranean climate (Camuffo et al., 2010a,b).

The temperature in Spain is reported in Fig.7 and refers only to the long time series of Cadiz-S. Fernando. The plots show that autumn and winter months experienced a colder period that reached the minimum around 1850. Spring and summer months are linearly interpolated with no trends but with some persistent swings alternating colder and warmer periods, with a marked warming in the most recent decades. However, the period of the GW, i.e. after 1980 is evident in the cold season and spring, more exactly from November to June, but it is not dissimilar from other previous warm periods, and it is not the warmest one in the Spanish series.

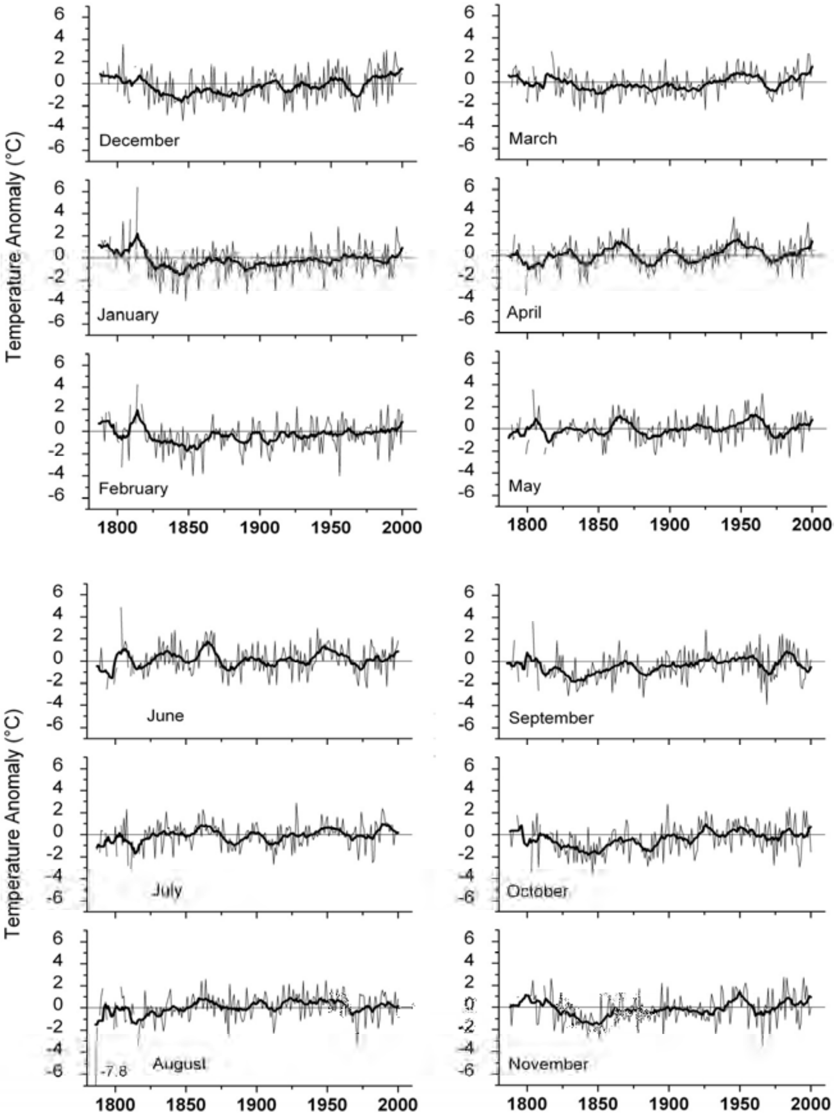

Fig. 7. Monthly temperature anomaly (°C) from instrumental data in Spain. The zero level corresponds to the average of the 1961-1990 reference period. Thin black lines refer to instrumental observations, thick black lines to 11-year running averages.

In Southern France (Fig.8), December and January undergone a change in temperature around 1900, passing from colder to milder winters. On the other hand, from the beginning of the series to 1800, the warm season from May to September was warmer than the 1961-1990 reference period, reaching a maximum slightly after 1750 with temperature levels higher than today. All the months are characterized by absence of long period trends but include several warm-cold swings.

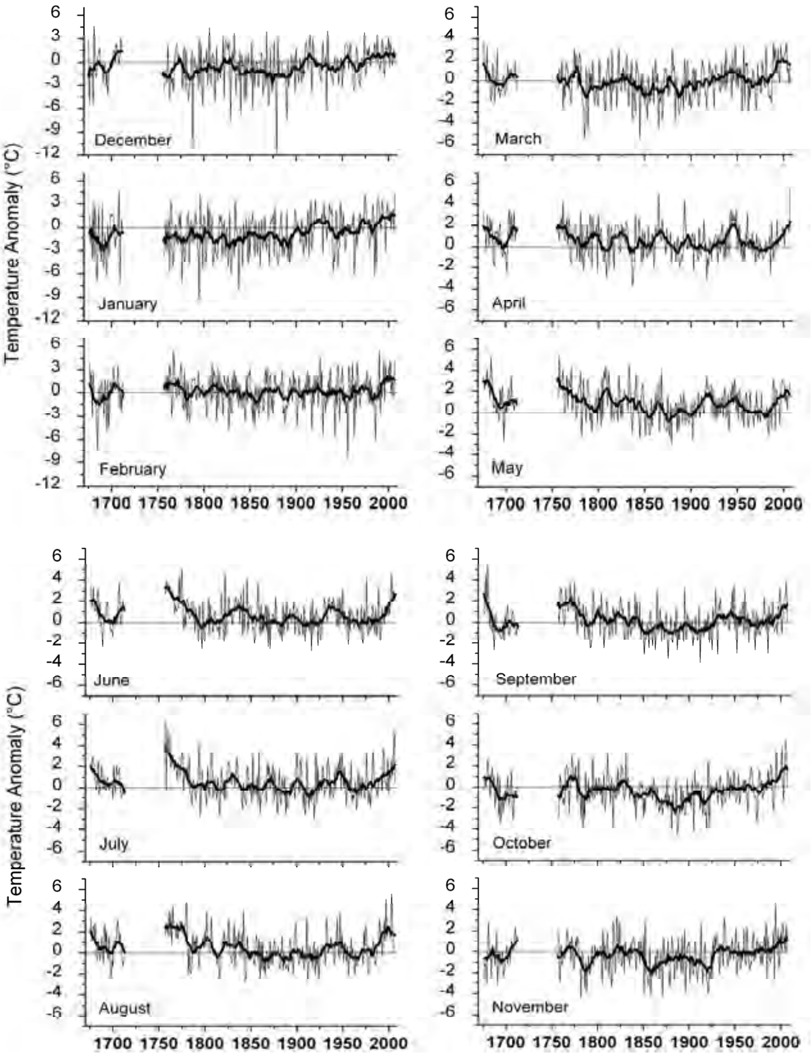

Fig. 8. Monthly temperature anomaly (°C) from instrumental data in Southern France. Zero level, thin and thick lines as in Fig.7.

In Northern-Central Italy (Fig.9) January, February and March show warming trends from 1739 to nowadays. No trends in other months. Warm-cold swings are evident in all months. In most months, and especially in May, June and August, the temperature increased after 1980 following the GW. However, around 1725-1730 the temperature was similar, or even higher than today in a number of months, i.e. May, September, October, November and December. The great winter in December 1738 and January 1739 is clearly visible; as opposed, the great winter 1929 with a deeper extreme in temperature the first half of February 1929 is not visible in the monthly averages being masked by the contribution of the second half of the month that was milder.

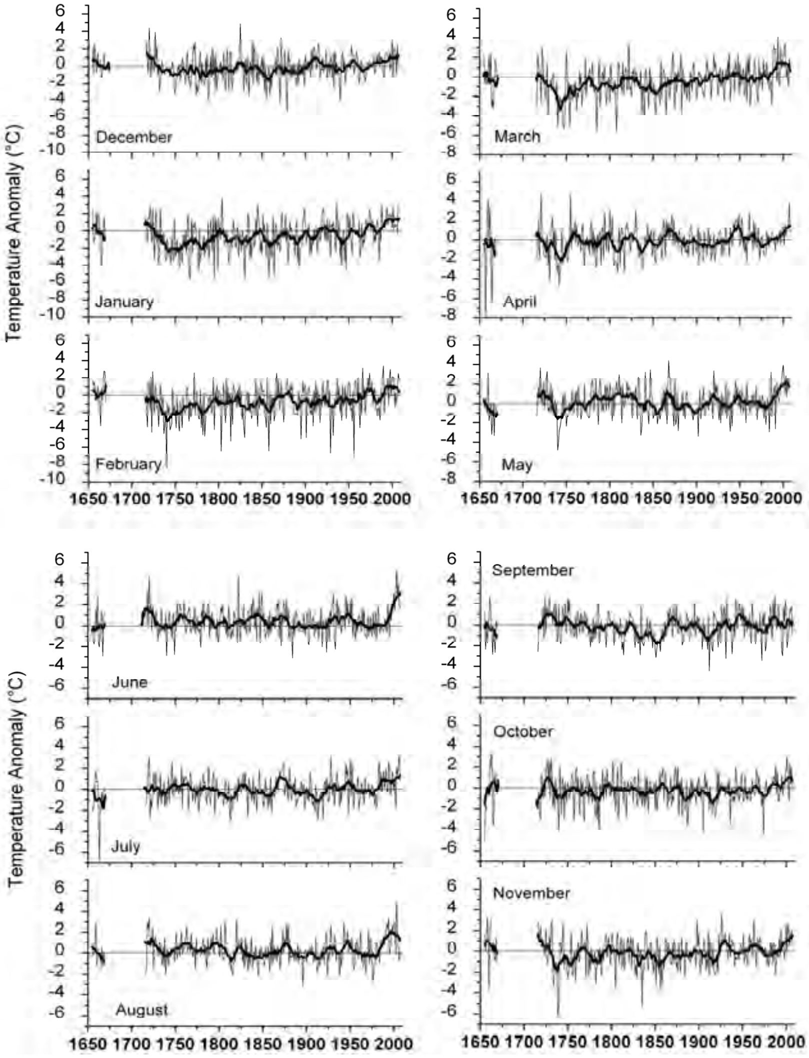

Fig. 9. Monthly temperature anomaly (°C) from instrumental data in Northern-Central Italy. Zero level, thin and thick lines as in Fig.7.

Southern Italy is located in the middle of the Mediterranean and its climate is strongly influenced by the difference between air and seawater temperature, differently from the Northern-Central part of the Italian Peninsula. The monthly temperature of Southern Italy is reported in Fig.10. The earliest period before 1800 is not homogeneous with the rest of the series and seems to overestimate the readings for some instrumental bias or relocation problem, and should be disregarded. The series seem more or less stationary till 1920, followed by a positive trend, i.e. increasing temperature. However, the most recent period, i.e. 1990-today, is not the warmest one in the series, maybe for the effect of change of phase of decadal swings or other chaotic factors.

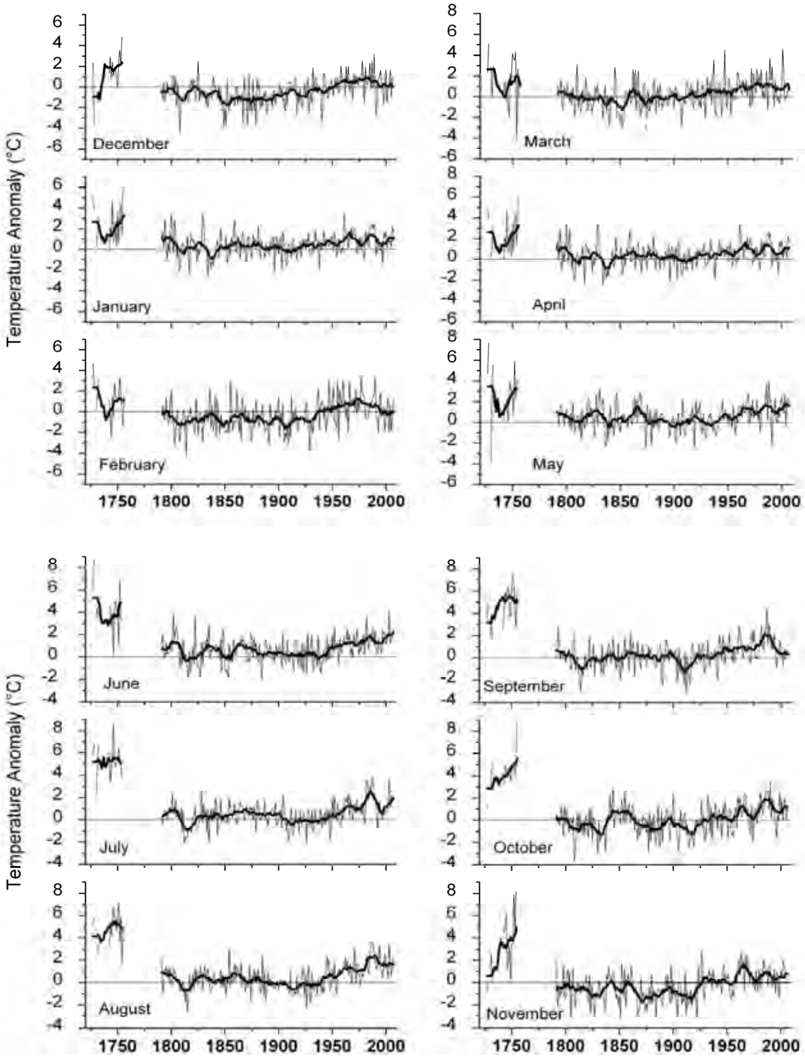

Fig. 10. Monthly temperature anomaly (°C) from instrumental data in Southern Italy. Zero level, thin and thick lines as in Fig.7.

4.3 Results from the instrumental observations of precipitation

The precipitation is presented in terms of anomaly as normalized ratio following the IPCC 2007 style (Le Treut et al., 2007). This style is particularly convenient in the case of arid regions, e.g. Spain and Southern Italy. The precipitation in the Mediterranean is characterized by large high-frequency variability, with irregular rainy-dry swings and 93 yr periodicity that has already been observed over the whole set of data (Camuffo et al., 2010a,b).

The precipitation in Portugal (Fig.11) is characterized by huge variability, with several extreme episodes from no rain at all to extremely intense rain episodes, in particular July and August exceeding in a number of episodes the average of the 1961-1990 reference period by an order of magnitude. The high frequency fluctuations are superimposed to a decadal swing. In the crucial last three decades of GW, i.e. after 1980, the situation is apparently contradictory, i.e. March, September and October seem to be characterised by positive trend, i.e. rainy; as opposed, February, May and July by negative trend, i.e. aridity, the other months having no or unclear trends.

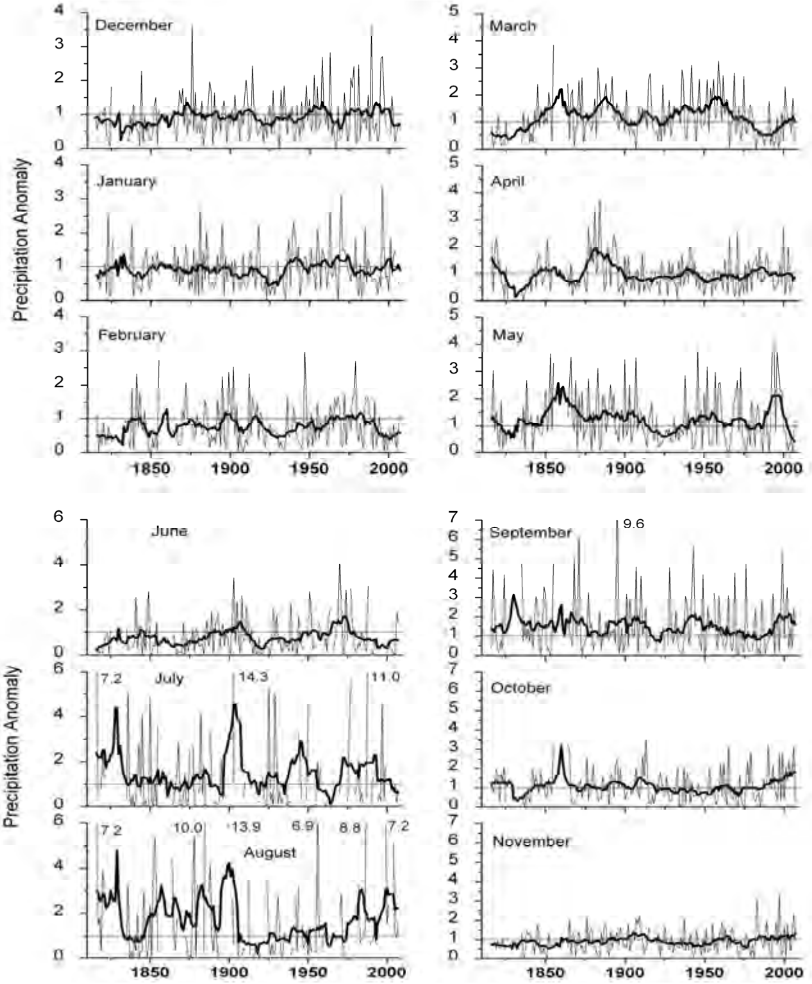

Fig. 11. Monthly precipitation anomaly from instrumental data in Portugal. Non dimensional units, the anomaly being expressed as a ratio with the 1961-1990 reference period. The 1-line level corresponds to the 1961-1990 average. Thin black lines refer to instrumental observations, thick black lines to 11-year running averages. Numbers on the side of peaks indicate the top level, external to the scale.

The precipitation (Fig.12) in all the Spanish stations shown in Fig.1 largely differs from month to month, including the reaction to the last three decades of GW, i.e. after 1980. In particular, February, March, April and July seem to go toward dryness; as opposed January, September and December toward wetness, the other months being unchanged or unclear. Some extreme episodes appear especially in June, July, August and September.

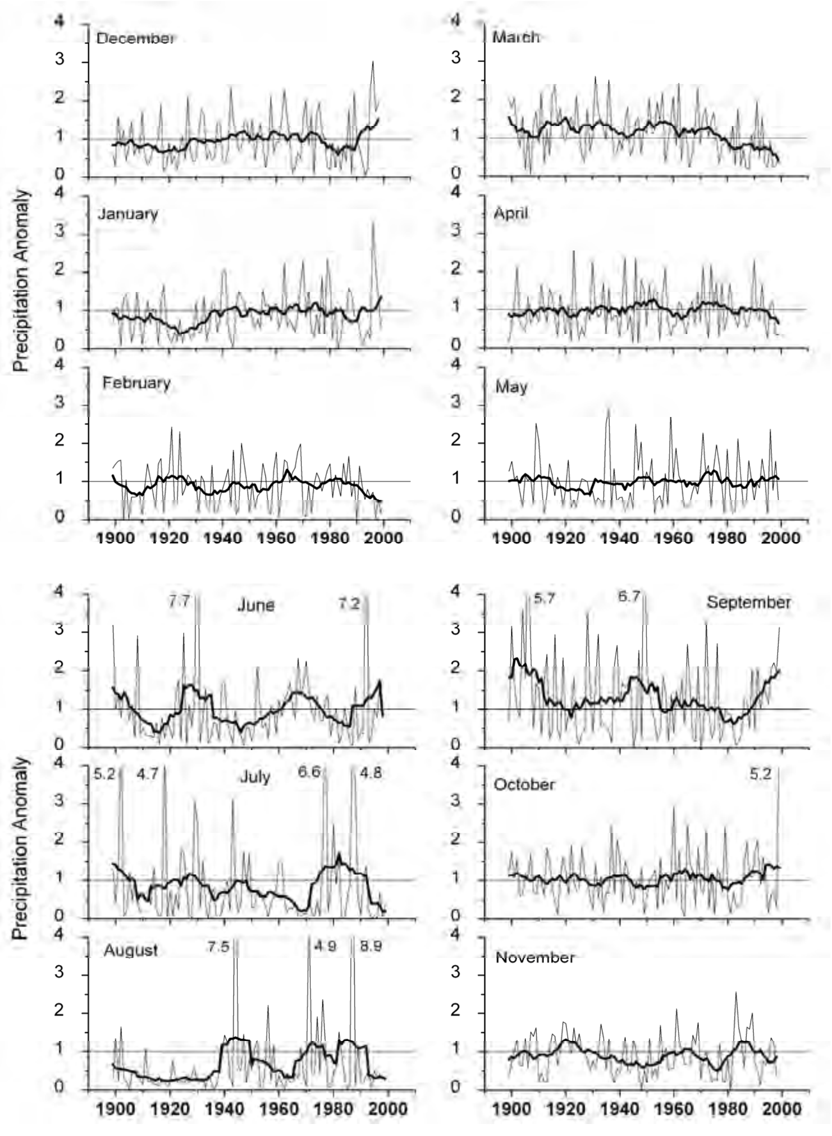

Fig. 12. Monthly precipitation anomaly from instrumental data in Spain. Units and symbols as in Fig.11.

The precipitation in Southern France (Fig.13) is more abundant in autumn, winter and spring, and less frequent in summer. All the monthly series are characterized by high frequency fluctuations and wet-dry swings for the whole period. December, January and February had less precipitation from the beginning of the instrumental records to 1900 and a wetter regime after 1900. The recent decades in the GW period are not characterized by any specific trends.

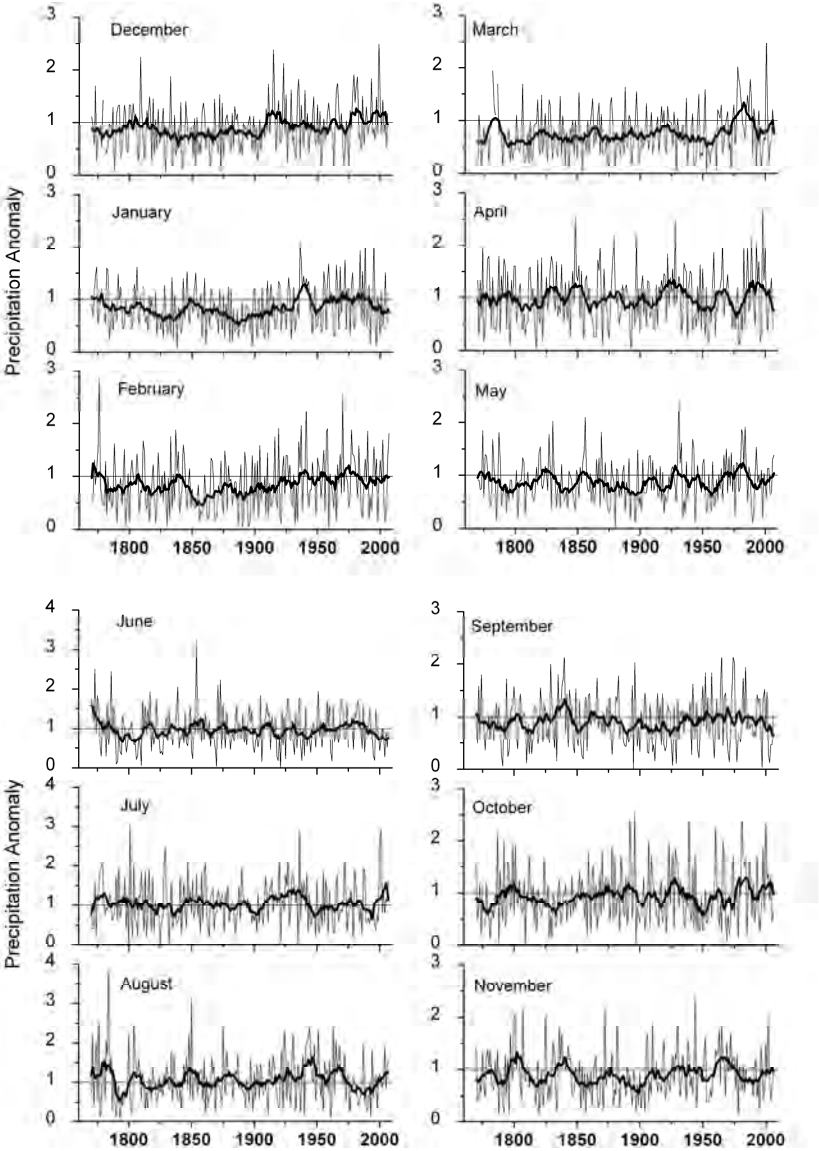

Fig. 13. Monthly precipitation anomaly from instrumental data in Southern France. Units and symbols as in Fig.11.

The rainy season in Northern Central Italy (Fig.14) is late spring (May-June) and autumn (October-November). In these months the series are almost regular from the statistical point of view, with high frequency fluctuations and some dry-wet decadal swings but no major changes. In general, peaks of abundant rain and episodes of aridity appear repeatedly, over the whole series. The last three decades of GW, i.e. after 1980, do not present any specific character.

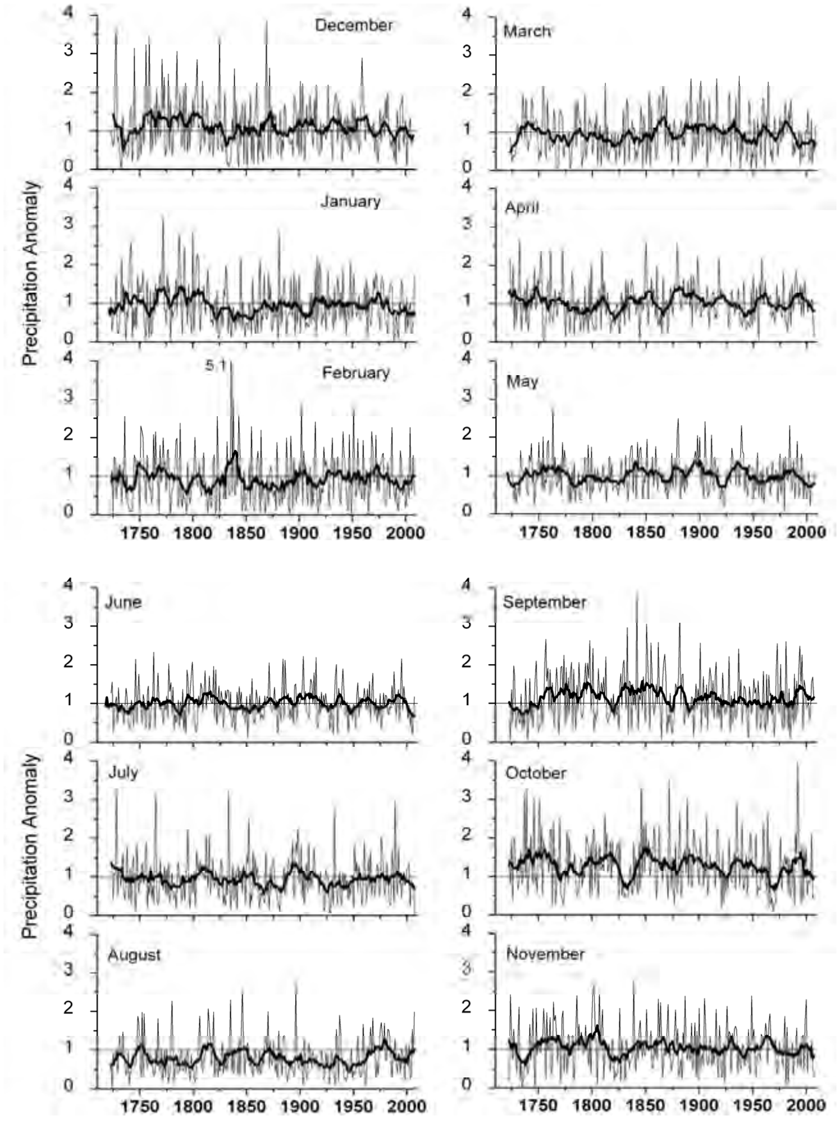

Fig. 14. Monthly precipitation anomaly from instrumental data in Northern-Central Italy. Units and symbols as in Fig.11.

The rainy season in Southern Italy (Fig.15) is the cold season, from October to April. The series are characterized by chaotically distributed short-term fluctuations and longer-term variability, with unclear or contradictory response to GW, especially after 1980. In this recent period, some months, e.g. June, September and December seem to be characterized by a positive trend, October and November by a negative one, the other months having no specific trends.

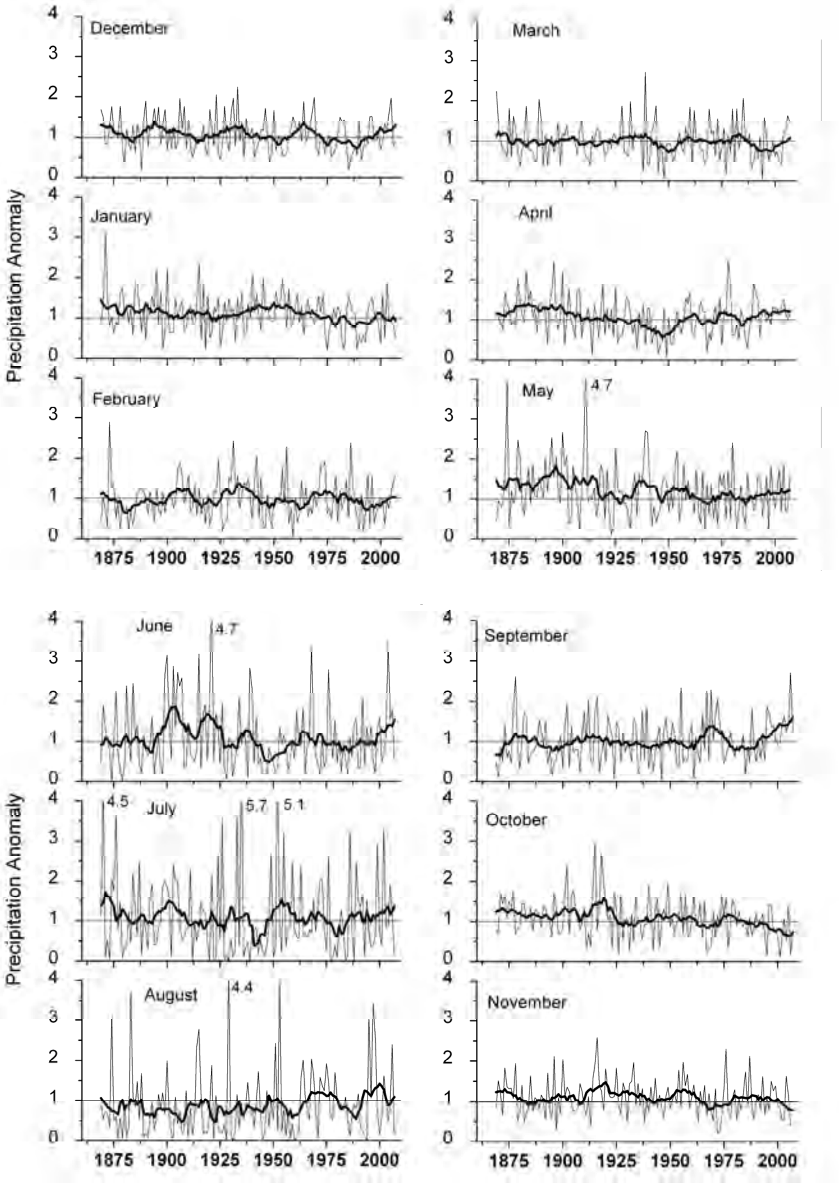

Fig. 15. Monthly precipitation anomaly from instrumental data in Southern Italy. Units and symbols as in Fig.11.

5. Biological proxies and the sea level rise

At Venice, regular tide gauge records are available since 1872 and show that the city is sinking at impressive rate, i.e. 2.4 mm yr^{-1} 1872-2009 average rate. Sinking is due to the combined effect of local land subsidence and sea level rise. The land subsidence is mainly due to tectonic drift, at constant rate, with some minor departures due to other factors, e.g. ground compaction, underground water extraction. The other key variable is the sea level rise for thermal expansion of the ocean water on the global scale (i.e. eustatic sea rise) and is expected to worsen for GW. The tide gauge measures the relative sea level (RSL), i.e. the sea level measured in relation with a frame fixed to the soil, that is a mobile reference.

The period before instrumental records is known after the fortunate combination of two available factors: a biological marker constituted by green algae, and their precise reproduction in some particular paintings. The methodology is simple. Buildings facing the canals have a green belt of algae living on walls at levels periodically reached by tides, and the belt front corresponds to the average of the high tides of the year. When the sea level changes, the green belt follows it by the same amount. The front of the algae on the Venice buildings was accurately reproduced by Paolo Caliari, nicknamed Veronese (1528-1588), and especially by the painters of Vedutas Giovan Antonio Canal, nicknamed Canaletto (1697-1768) and his nephew Bernardo Bellotto (1720-1780). All of them used a Camera Obscura as a tool to obtain precise reproductions of the views and were extremely accurate in reporting the algae levels as it has been verified with historical and statistical tests (Camuffo and Sturaro, 2003, 2004; Camuffo et al., 2005). After having determined the level of the algae as it was in the paintings, and how it is today, it is possible to obtain the RSL rise occurred in the meantime after the difference between the two levels.

The first painting useful to our aims is by Veronese and is dated 1571. It accurately reproduces the Coccina Palace, facing the Grand Canal, with people standing on the staircase that has five steps clear from algae. Nowadays the algae infest all the steps of this staircase. The height of each step is 18 cm, so that the algae belt has displaced by 5×18 cm = 90 cm. We should, however, correct this finding for two factors that have caused an additional rise of the algae belt. The first factor is that modern motorboats generate waves higher than the rowboats in use at the XVIII century. The difference in wave height was assessed after wave gauge monitoring in the Grand Canal during normal business days and in the occasion of the '*Regatta*', i.e. the historical happening repeated every year, in which accurate replicas of rowboats and characters from the XVIII century rowing on the Grand Canal as in the times of the Venice Republic, ended 1797. The result was 5 cm additional wall wetting for motorboat waves. The second factor is the dynamic increase of the tidal wave for the excavation of deep and wide canals in the Lagoon and was evaluated to cause 3 cm additional wetting. If we subtract to the finding after the Veronese painting the 8 cm for the above corrections, we get RSL = 82±9 cm where we have attributed the uncertainty of one step, i.e. ±9 cm (Camuffo, 2010). The result from twelve Canaletto and Belotto paintings with the algae belt clearly visible was that the RSL rose by 69±11 cm. After having subtracted 8 cm for the above corrections, the bulk submersion of Venice, i.e. the RSL estimated from the Canaletto and Bellotto paintings is 61±11 cm.

If we combine in the same graph the 1872-2010 tide gauge record in Venice with the biological proxies related to the tide level in 1571, i.e. Veronese, and around 1750, i.e. Canaletto and Bellotto, we can assess the past sea level at Venice back to 1571 as summarized in Fig.16.

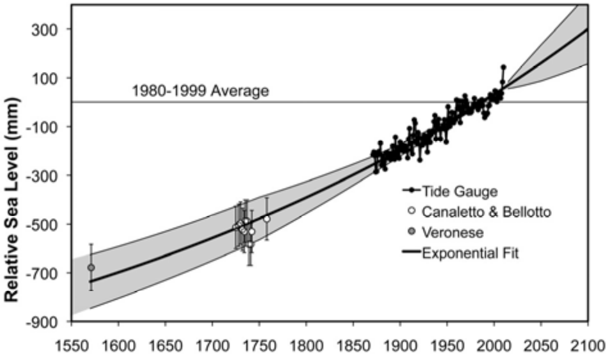

Fig. 16. Relative sea level (RSL) in Venice. Small black dots: tide gauge readings; white circles: proxies from Canaletto and Bellotto paintings; grey circle: proxy from Veronese painting. Thick black line: exponential interpolation with equation RSL = 71.196 exp (0.0016 X) where X is the year AD; thin grey lines: 95% confidence interval.

In the period from Veronese to Canaletto the average yearly trend is 1.2 mm yr^{-1}; from Canaletto to nowadays the average yearly trend is 1.9 mm yr^{-1} (Camuffo and Sturaro, 2003, 2004; Camuffo et al., 2005). The tide gauge and the displacement of the algae front show that the relative sea level has increased at exponential rate (i.e. acceleration for increasing thermal expansion) over the last five centuries. This is a real problem for the city.

A dramatic consequence of SLR is that exceptionally high tides, i.e. surges generated by the Sirocco wind when a low pressure lies in the western Mediterranean, become more and more frequent, with seawaters flooding Venice. Flooding tides, locally called "*acqua alta*" invade the lowest part of the city when the sea water exceeds 110 cm above the average tide level in 1897 established as a reference. The long series of flooding surges from documentary sources for the 792–1867 period (Camuffo, 1993; Enzi and Camuffo, 1995), combined with the tide- gauge records for the 1872–2010 period, show that the frequency of the flooding tides too is exponentially increasing (Fig.17).

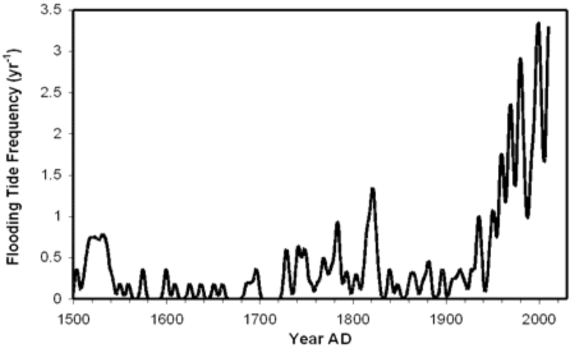

Fig. 17. Occurrence of the flooding tides (i.e. sea level 110 cm higher than the average in 1897) at Venice over the last 500 years. The graph reports the number of independent floods, i.e. one flooding tide per surge disregarding the short-term interruptions and repetitions for the astronomical tide modulation.

6. Conclusions

This Chapter has presented the trends in temperature, precipitation and sea level rise over the last five centuries, i.e. from the Medieval Optimum to the present-day GW.

The air temperature series do not provide clear evidence for marked increasing trends over the long period (e.g. one or more centuries), except for the recent GW over the last 30-40 years (Le Treut et al., 2007). Short term fluctuations and decadal or pluridecadal cycles are not a novelty for the Mediterranean. All the series show that both the temperature and the precipitation are characterized by repeated swings. Individual swings may differ in amplitude and duration, depending on the historical period. In previous papers it has been demonstrated that the periodicity of temperature is 12.7, 26.5, 34.4 and 57.3 years (Camuffo et al., 2010a,b). In conclusion, it is probable that the Mediterranean temperature will not increase like a hockey stick as expected for the GW over the Northern Hemisphere but will continue to swing maybe in association with the GW trends.

The precipitation series too are characterized by huge variability, not by specific decreasing trends. Decadal dry-wet swings are chaotically distributed and disappear for the change of phase when common periodicities are searched in the whole set of data, except for the 90 year period (Camuffo et al., 2010a,b). Air temperature and precipitation evolve in an apparently independent way, changing in phase and having correlation coefficient variable over time. This means that the two phenomena are not fully controlled by the same forcing factors. The crucial factor is that air temperature and precipitation are related between each other through the action of the sea, and the mechanism will depend on the thickness of the thermocline and the resulting Sea Surface Temperature (SST). The Mediterranean water constitutes a huge reservoir of heat, and the weather conditions depend on the seawater temperature profile i.e. the thermocline. In the case summer and early autumn have been relatively calm, the summer has accumulated heat near the surface, forming a thin, warm layer and the higher SST will start earlier and will favour the rainy season. On the other hand, if the summer had a violent storm with high waves that mixed the surface waters and deepened the thermocline redistributing in depth the heat, the SST will be lower and the winter rains will be less. In conclusion, any feedback governed by a number of interacting factors will necessarily be complex because of the chaotic variability in correlation and phase, making difficult any forecast.

Swings and chaos make obscure any tendency that may derive from the GW. Today temperature and precipitation have opposing trends, i.e. hot and dry. However, the observations suggest that no any combination is stable and persistent for a long time. Today we see hot and dry, but in the past we also had hot and wet, cold and wet and cold and dry periods. The observations suggest that the local climate system is not characterized by any stable equilibrium and in the future it will continue to swing and change temperature and precipitation coupling.

Although the temperature in the Mediterranean will increase less than in the Northern Hemisphere, nevertheless the thermal expansion of oceanic waters on the global scale will govern the water fluxes through the Gibraltar Strait, increasing the level of the Mediterranean Sea and flooding the coastal areas. The problem will be especially relevant in the areas affected by land subsidence because of the synergistic effect of both factors. The most famous example is the city of Venice, where the local sea level, observed over the last 500 years, is exponentially increasing and the expectation by 2100 will likely be 30 cm higher than the 1980-1999 average level. In the future, the most dramatic impact will affect historical buildings. The problem is that the Venice buildings originally had an impermeable basement and a protruding protection against splashing waves. At present, the protective elements sunk below the average high tide level, with the consequence that walls are impregnated with seawater, with internal migration of NaCl and crystallisation cycles which loose rendering, destroy mortars, bricks and stones. Briefly, this is a tremendous, powerful mechanism that is destroying at slow rate all buildings reached by seawaters.

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8. References

Alcoforado, M.J., Nunes, M.F., & Garcia, J.C. (2000). Temperature and precipitation reconstruction in southern Portugal during the late Maunder Minimum (AD 1675-1715). *The Holocene*, Vol. 10, No. 3, (April 2000), pp. (333-340)

Barriendos, M. (1997). Climatic variations in the Iberian Peninsula during the late Maunder Minimum (AD 1675-1715): an analysis of data from rogation ceremonies. *The Holocene*, Vol. 7, No. 1, (March 1997), pp. (105-111)

Barriendos, M., & Llasat, M.C. (2003). The Case of the `Maldá' Anomaly in the Western Mediterranean Basin (AD 1760–1800): An Example of a Strong Climatic Variability. *Climatic Change*, Vol. 61, No. 1-2, (November 2003), pp. (191-216)

Barriendos, M. (2005). Climate and Culture in Spain. Religious Responses to extreme Climatic Events in the Hispanic Kingdoms (16th-19th c). In: *Kulturelle Konsequenzen der "Kleinen Eiszeit"*, Behringer W, Lehmann H, Pfister C (ed.), Vandenhoeck & Ruprecht, Göttingen

Bolle, H.J. (2003). *Mediterranean Climate*, Springer-Verlag, Berlin

Brazdil, R., Glaser, R., Pfister, C., Dobrovolny, P., Antoine, J.M., Barriendos, M., Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., Kotyza, O., & Rodrigo, F.S. (1999). Flood Events of Selected European Rivers in the Sixteenth-Century. Special Issue: Climatic Variability in Sixteenth-Century Europe and Its Social Dimensions. *Climatic Change*, Vol. 43,No. 1, (September 1999), pp. (239-285)

Brázdil, R., Pfister, C., Wanner, H., von Storch, H., & Luterbacher, J. (2005). Historical climatology in Europe – The State of the Art. Climatic Change, Vol. 70, No. 3, (June 2005), pp. (363-430)

Brázdil, R., Dobrovolný, P., Luterbacher, J., Moberg, A., Pfister, C., Wheeler, D., & Zorita, E. (2010). European climate of the past 500 years: new challenges for historical climatology. *Climatic Change*, Vol. 101, No. 1, (May 2010), pp. (7-40)

Camuffo, D. (1993). Analysis of the Sea Surges at Venice from A.D. 782 to 1990. *Theoretical and Applied Climatology*, Vol. 47, pp. (1-14)

Camuffo, D. (2002). History of the long series of the air temperature in Padova (1725-today). *Climatic Change*, Vol. 53, No. 1-3, (April 2002), pp. (7-76)

Camuffo, D. (2010). Le niveau de la mer à Venise d'après l'œuvre picturale de Véronèse, Canaletto et Bellotto. Révue d'Histoire Moderne et Contemporaine, Vol. 57, No. 3, pp. (92-110)

Camuffo, D., & Bertolin, C. (2011). The earliest temperature observations in the world: the Medici Network (1654–1670). *Climatic Change*, DOI 10.1007/s10584-011-0142-5

Camuffo, D., & Enzi, S. (1992a). Critical Analysis of Archive Sources for Historical Climatology of Northern Italy, In: *European Climate Reconstructed from Historical Documents: Methods and Results*. Frenzel B., Paleoclimate Research, Special Issue 7, Fischer Verlag, Stuttgart

Camuffo, D., & Enzi, S. (1992b). Reconstructing the Climate of Northern Italy from Archive Sources, In: *Climate since 1500 A.D.*. Bradley RS, Jones PD (eds.) Routledge, London

Camuffo, D., & Enzi, S. (1994). The Climate of Italy from 1675 to 1715, In: *Climatic Trends and Anomalies in Europe 1675-1715.* Frenzel B., Paleoclimate Research, Special Issue 8, Fischer Verlag, Stuttgart

Camuffo, D., & Enzi, S. (1996). The Analysis of two Bi-millenary Series: Tiber and Po River Floods, In: *Climatic Variations and Forcing Mechanisms of the last 2000 years*, Jones P.D., Bradley R.S., Jouzel J., NATO ASI Series, Series I: Global Environmental Change, Vol. 41, Springer Verlag, Stuttgart

Camuffo, D., & Jones, P. (2002). *Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources*. Kluwer Academic Publishers, Dordrecht, Boston, London

Camuffo, D., & Sturaro, G. (2003). Sixty-cm submersion of Venice discovered thanks to Canaletto's paintings. *Climatic Change*, Vol. 58, No. 3, (June 2003), pp. (333-343)

Camuffo, D., & Sturaro, G. (2004). Use of proxy-documentary and instrumental data to assess the risk factors leading to sea flooding in Venice. *Global and Planetary Change*, Vol. 40, pp (93-103)

Camuffo, D., Pagan, E., & Sturaro, G. (2005). The extraction of Venetian sea-level change from paintings by Canaletto and Bellotto, in: *Flooding and Environmental Challenges for Venice: State of Knowledge*, Fletcher C.A. & Spencer T., pp. (129-140), Cambridge University Press, Cambridge

Camuffo, D., Bertolin, C., Barriendos, M., Dominguez-Castro, F., Cocheo, C., Enzi, S., Sghedoni, M., della Valle, A., Garnier, E., Alcoforado, M.J., Xoplaki, E., Luterbacher, J., Diodato, N., Maugeri, M., Nunes, M.F., & Rodriguez, R. (2010a). 500-year temperature reconstruction in the Mediterranean Basin by means of documentary data and instrumental observations. *Climatic Change*, Vol. 101, No. 1-2, (July 2010), pp. (169-199)

Camuffo, D., Bertolin, C., Diodato, N., Barriendos, M., Dominguez-Castro, F., Cocheo, C., della Valle, A., Garnier, E., & Alcoforado, M.J. (2010b). The Western Mediterranean Climate: how will it respond to Global Warming? *Climatic Change*, Vol. 100, No. 1, (May 2010), pp. (137-142)

Chine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., & Le Roy Ladurine, E, (2004). Grape ripening as a past climate indicator. *Nature* ,Vol. 432, No. 7015, (November 2004), pp. (289-290)

Dominguez-Castro, F., Santisteban, J.I., Barriendos, M., & Mediavilla, R. (2008). Seasonal reconstruction of drought episodes for central Spain from rogation ceremonies re.corded at Toledo Cathedral from 1506 to 1900: a methodological approach. *Global and Planetary Changes*, Vol. 63, pp (230–242)

Enzi, S., & Camuffo, D. (1995). Documentary sources of the sea surges in Venice from A.D. 787 to A.D. 1867. *Natural Hazards*, Vol. 12, No. 3, (November 1995), pp. (225-287)

Fletcher, C.A., & Spencer, T. (2005). *Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge*. Cambridge University Press, Cambridge

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brazdil, R., Bertolin, C., Camuffo, D., Deutsch, M., Dobrovolny, P., Engelen van, A., Enzi, S., Halićhová, M., Koenig, S., Kotyza, O., Limanowka, D., Macková, J. & M. Sghedoni. 2010. The variability of European floods since AD 1500. *Climatic Change*, Vol. 101, No. 1-2, (July 2010), pp. (235-256).

Jeftic, L., Milliman, D.J., & Sestini, G. (1992). *Climatic Change and the Mediterranean*. Edward Arnold, London

Jurin, J. (1723) . Invitatio ad observationes Meteorologicas communi consilio instituendas a Jacobo Jurin M.D. Soc. Reg. Secr. et Colleg. Med. Lond. Socio. *Philosophical Transactions,* Vol. 379, pp. (422-427)

Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., & Prather, M. (2007). Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment* Report of the Intergovernmental Panel on Climate Change, Solomon S., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., & Miller H.L., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Lionello, P., Malanotte-Rizzoli, P., & Boscolo, R. (2006). *The Mediterranean Climate: an overview of the main characteristics and issues*. Elsevier, Amsterdam

Luterbacher, J., Xoplaki, E., Casty, C., Wanner, H., Pauling, A., Kuettel, M., Rutishauser, T., Broennimann, S., Fischer, E., Fleitmann, D., Gonzalez-Rouco, J.F., Garcìa-Herrera, R., Barriendos, M., Rodrigo, F.S., Gonzalez-Hidalgo, J.C., Saz, M.A., Gimeno, L., Ribera, P., Brunet, M., Paeth, H., Rimbu, N., Felis, T., Jacobeit, J., Duenkeloh, A., Zorita, E., Guiot, J., Turkes, M., Alcoforado, M.J., Trigo, R., Wheeler, D., Tett, S.F.B., Mann, M.E., Touchan, R., Shindell, D.T., Silenzi, S., Montagna, P., Camuffo, D., Mariotti, A., Nanni, T., Brunetti, M., Maugeri, M., Zerefos, C., De Zolt, S., Lionello, P., Nunes, M.F., Rath, V., Beltrami, H., Garnier, E., & Le Roy Ladurie, E. (2006). Mediterranean climate variability over the last centuries: A review, In: *The*

Mediterranean Climate: an overview of the main characteristics and issues, Lionello P., Malanotte-Rizzoli P., Boscolo R., Elsevier, Amsterdam, the Netherlands

Luterbacher, J., Koenig, S.J., Franke, J., van der Schrier, G., Della-Marta, P.M., Jacobeit, J., Küttel, M., Gonzalez-Rouco, F.J., Zorita, E., Xoplaki, E., Stössel, M., Rutishauser, T., Wanner, H., Pfister, C., Brázdil, R., Dobrovolný, P., Camuffo, D., Bertolin, C., Moberg, A., Leijonhufvud, L., Söderberg, J., Allan, R., Wilson, R., Wheeler, D., Barriendos, M., Glaser, R., Riemann, D., Nordli, O., Limanówka, D., van Engelen, A., & Zerefos, C.S. (2010). Circulation dynamics and its influence on European and Mediterranean January-April climate over the past half millennium: Results and insights from instrumental data, documentary evidence and coupled climate models *Climatic Change*, Vol. 101, No. 1-2, (July 2010), pp. (201-234)

Magalotti, L. (1666). *Saggi di naturali esperienze fatte nell'Accademia del Cimento*, Giuseppe Cocchini, Florence

Martín Vide, J., & Barriendos, M. (1995). The use of rogation ceremony records in climatic reconstruction: a case study from Catalonia (Spain). *Climatic Change*, Vol. 30, No. 2, (June 1995), pp. (201-221)

Pfister, C., Brazdil, R., Glaser, R., Barriendos, M., Camuffo, D., Deutsch, M., Dobrovolny, P., Enzi, S., Guidoboni, E., Kotyza, O., Militzer, S., Racz, L., & Rodrigo, F.S. (1999). Documentary Evidence on Climate in the Sixteenth-Century Europe. *Climatic Change,* Vol. 43, No. 1, (September 1999), pp. (55-110)

Piervitali, E., & Colacino, M. (2001). Evidence of drought in Western Sicily during the period 1565-1915 from Liturgical Offices. *Climatic Change*, Vol. 49, No. 1-2, (April 2001), pp. 225-238

Reiter, E.R. (1975). *Weather Phenomena of the Mediterranean Basin*. EPRFNPS, Montrey, California

Rodrigo, F.S., & Barriendos, M. (2008) . Reconstruction of seasonal and annual rainfall variability in the Iberian Peninsula (16th – 20th Centuries) from documentary data. *Global and Planetary Changes* ,Vol 63, pp (243–257) doi:10.1016/j.gloplacha.2007.09.004

Targioni Tozzetti, G. (1780). *Notizie degli aggrandimenti delle Scienze Fisiche accaduti in Toscana nel corso di anni LX del secolo XVII*. Tomo I. Bouchard, Florence

UK Meteorological Office (1962). *Weather in the Mediterranean*. Her Majesty Stationery Office, London

Xoplaki, E., Gonzalez-Rouco, F.J., Luterbacher, J., & Wanner, H. (2003). Mediterranean Summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. Climate Dynamics, Vol. 20, No. 7-8, (May 2003), pp. (723-739)

Xoplaki, E., Gonzalez-Rouco, J.F., Luterbacher, J., & Wanner, H. (2004), Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. Climate Dynamics, Vol. 23, No. 1, (August 2004), pp. (63-78)

Wallén, C.C. (1970). Climates of Northern and Western Europe, Elsevier, Amsterdam

Wallén, CC. (1977) . Climates of Central and Southern Europe. Elsevier, Amsterdam