Evolving flood patterns in a Mediterranean region (1301-2012) and climatic factors. The case of Catalonia.

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Abstract

Data on flood occurrence and flood impacts for the last seven centuries in the northeast Iberian Peninsula have been analysed in order to characterise long-term trends, anomalous periods and their relationship with different climatic factors such as precipitation, general circulation and solar activity. Catastrophic floods (those that produce complete or partial destruction of infrastructure close to the river, and major damages in the overflowed area, including some zones away from the channels) do not present a statistically significant trend, whereas extraordinary floods (the channel is overflowed and some punctual severe damages can be produced in the infrastructures placed in the river course or near it, but usually damages are slight), have seen a significant rise, especially from 1850 on, and were responsible for the total increase in flooding in the region. This rise can be mainly attributed to small coastal catchments, which have experienced a marked increase in developed land and population, resulting in changes in land use and greater vulnerability. Changes in precipitation alone cannot explain the variation in flood patterns, although a certain increase was shown in late summer-early autumn, when extraordinary floods are most frequently recorded. The relationship between North Atlantic circulation and floods is not as strong, due to the important role of mesoscale factors in heavy precipitation in the northwest of the Mediterranean region. However, it can explain the variance to some extent, mainly in relation to the catastrophic floods experienced during the autumn. Solar activity has some impact on changes in catastrophic floods with cycles related to the Quasi-Biennial Oscillation and the

Gleissberg solar cycle. In addition, anomalous periods of high flood frequency in autumn generally occurred during periods of increased solar activity. The physical influence of the latter in general circulation patterns, the high troposphere and the stratosphere, has been analysed in order to ascertain its role in causing floods.

1 Introduction

Floods are the natural hazard with the largest socio-economic impact in the world, and they are responsible for the highest number of deaths and the most damage caused by natural hazards worldwide (Munich Re, 2006; IPCC, 2012). This problem is exacerbated by the acceleration of the hydrological cycle and other extreme events, which are considered a consequence of climate change. Some studies show that water extremes (floods and droughts), which currently have a return period of 100 years, may recur every 10 to 50 years by 2070 in some regions in Europe (Lehner et al., 2006). Precipitation intensity is also projected to increase in some regions, leading to more flooding (Dankers and Feyen, 2009). However, keeping the previous IPCC assessment report in mind (IPCC, 2013), these results are not representative enough for a full understanding of the impact of climatic change on future floods, due to the complexity of the different factors involved in causing floods and the impact they have, as well as significant questions about future changes to precipitation.

With regard to present trends in precipitation extremes and floods, the latest IPCC report on extremes (IPCC, 2012) states that there is “limited to medium” evidence available to assess climate-driven changes to the magnitude and frequency of floods on a regional scale, with “low agreement” evidence and “low confidence” on a global scale for the signs of said changes. In the case of the Iberian Peninsula (IP) there are some controversial results, as for the rest of the Mediterranean area, with regard to signs of changes in precipitation. This is due to the diverse periods considered by different authors, the regions in question, and the varying approaches taken as the methodology applied (Barrera and Llasat, 2004; Llasat and Quintas, 2004; González-Hidalgo et al., 2009; Pryor et al., 2009; Turco and Llasat, 2011). Some of them point to a decrease in the intensity of daily precipitation and an increase in the number of days with light rain (García et al., 2007; Rodrigo and Trigo, 2007; Rodrigo, 2010; López-Moreno et al., 2010) for much of the Iberian Peninsula. On the contrary, other studies show that less-intensive rainy days are more frequent and intensive precipitation episodes have increased along the Mediterranean coast (Alpert et al., 2002; Goodess and Jones, 2002), but that these results cannot be generalised (Altava-Ortiz et al., 2010). These findings are consistent with the "low-agreement" findings of the IPCC (2012), which is notable in the Mediterranean region where mesoscale mechanisms and convective precipitation play a major role in the temporal and spatial distribution of precipitation.

Apart from the low significance and agreement in precipitation trends, the complexity associated with flooding requires further analysis of the relationship between changes to floods and rainfall, and the evolution of climatic and hydrologic parameters (Di Baldassarre et al., 2009; Heine and Pinter, 2012; Remo et al., 2012; Hall et al., 2014). Most of these authors stress the importance of changes to land use (Naef et al., 2002), or possible changes in runoff coefficients (Sivapalan et al., 2005; Mouri et al., 2011). In short, and as indicated by Mertz et al., (2012), changes to the river itself, to the basin and to the atmosphere should be considered as possible physical causes for the changes to the flood regime. The problem is exacerbated when flood series are built from proxy data (i.e. flood impacts), where case factors such as vulnerability, exposure and perception play a more important role. For instance, the trends observed in changes to floods in the northwest of the Mediterranean Region could be related principally to changes in vulnerability and land use, and also to changes in perception and exposed assets (Barrera et al., 2006; Barredo et al., 2012; Llasat et al., 2013).

Historical flood evidences are mainly based on the impact descriptions and, consequently, they refer to the floods as a holistic risk, being difficult to separate the "natural" causes from the rest. The flood chronologies that can be constructed from instrumental records and flow series for Europe do not usually extend further back than the 19th century (the 20th century for Spain). Flood historical records can arrive until the 14th century, except for those in Italy dating from the Roman Empire. Besides this, information density in past is heterogeneous, not only due to the lack of records (i.e. Macdonald, 2014), but also due to the relative youth of the science that encompasses historical climatology with the modern understanding of climate dynamics, meteorology and hydrology (Glaser, 1996; Camuffo and Enzi, 1996; Brázdil et al., 1999; Lang and Cœur, 2002). The major documentary historical sources containing climatic information and details of its effects are local and state government records, religious collections, private collections, notaries' archives and taxation records (Barriendos et al., 2003; Brázdil et al., 2014). Whenever possible, the historical flood classification should be based on discharge estimates, with a sensitivity analysis to assess the specific errors of the hydraulic model for the conversion of historical flood levels into discharge (Brázdil et al., 2006; Herget et al., 2014). On the contrary, in order to have the longest possible flood series, a scale of event magnitude can be proposed using the effects of the floods on the river channel system and surrounding areas. This is the approach more commonly used (Llasat et al., 2005; Barriendos et al., 2014; Retsö, 2014). In this sense, the objective of the FLOODCHANGE project is to improve at European scale the built of long historical flood records in order to build a flood-change model (http://floodchange.hydro.tuwien.ac.at/deciphering-river-flood-change/). We would like to address the reader to the papers published in this special issue to find more details about historical floods data and their analysis (Kiss et al., 2014).

In this context, analysis of long-term homogeneous flood series and the corresponding causes is necessary in order to have a better understanding of how they evolve. That is the aim of this paper. Subsequently, based on early works on the evolution of floods in the northeast of the IP from the 14th century until 2002, the historical flood database of Catalonia (North-eastern Spain) has been updated until 2012 to review and identify any significant long-term trends or anomalies, and to analyse the potential relationship with climatic and non-climatic factors. This database, together with data on precipitation and information on solar activity and general circulation, is presented in Sect. 2. The methodology on building flood index series and carrying out statistical analysis on the same is explained in Sect. 3. Finally, the main results obtained on flood evolution and the potential relationship between the same and different climatic factors is presented and discussed in Sect. 4.

2 Area of study and data

Catalonia (northeast Spain) is characterised by a complex topography that has a considerable impact on the region's climatology and atmospheric circulation patterns: there are two mountain ranges with average heights of around 500 m a.s.l. (littoral zone) and 1,500 m a.s.l. (pre-littoral zone), located parallel to the coastline, and the Pyrenees, with summits above 3,000 m a.s.l. (Fig. 1). These orographic factors, together with the influence of the Mediterranean Sea and the associated Mediterranean Air Mass (Jansà, 1997), as well as the Atlantic influence on the northwestern side of the region, produce high climatic and meteorological contrasts between the different areas. Subsequently, precipitation is characterised by significant spatial and temporal variability. Annual-mean rainfall varies from 400 mm in the south to 1,300 mm in the north, while extreme daily values can surpass 300 mm, mainly in areas located near the coast or in the Pyrenees.

Heavy rainfall is usually due to convective precipitation normally caused by mesoscale systems and multicellular structures that occur in the late summer, autumn and spring. While isolated thunderstorms associated with convective events are a typical feature of summer weather, convection embedded in stratiform precipitation associated with slight convective events is more frequent during late autumn and winter (Llasat, 2001; Rigo and Llasat, 2004; Barnolas et al., 2010). The annual cycle of convective rainfall shows that maximum levels fall between May and November, with the highest rainfall in August at 64% of convective precipitation (Llasat et al., 2007).

As a result, this region frequently experiences floods. More than 40% of municipalities in Catalonia have a high or very high flood risk, according to INUNCAT, a Civil Protection Plan covering Flood Risks in Catalonia (DGPC, 2012). Generally, flash floods have an impact on coastal torrential basins and cause some level of damage. They are associated with highly convective and locally concentrated heavy rainfall where accumulated precipitation does not surpass 100 mm. On certain occasions, heavy rainfall produced by multicellular or mesoscale systems can be more extensive in terms of duration and area covered, producing more than 200 mm in less than 3 hours or surpassing 400 mm in 24 hours. The coastal fringe, where the majority of the population is concentrated, is the most flood-prone area due to the presence of numerous small torrential catchments, delta plains and river or stream mouths (Barnolas and Llasat, 2007). In these populated areas the relationship between human activity and flooding (in terms of the environment, land use changes, vulnerability, etc.) is very complex. In addition, some of the catchments are characterised by a non-permanent flooding regime, which means it is not possible to gauge data on discharge flows.

In this paper we have used flood chronologies for the Ebro, Segre, Ter and Llobregat rivers, the Maresme and Barcelona regions (with non permanent flow), which are representative of the key climatic and hydrological regions within Catalonia (Fig. 1). Data measured from the 14th century until 2002 was provided within the framework of the SPHERE project (EVG1-CT-1999-00010, Barriendos et al., 2003; Llasat et al., 2005). This database has been updated to cover until the year 2012, following the Ph.D. by Barrera-Escoda (2008) and research carried out by the authors until the present day. Flood data has been obtained from documentary sources (from the 14th to the 20th century), and newspapers and technical reports (from the end of 19th century). Flood data basically consists of the recorded date for the flood and details of the damage caused. The locations of all of the flood series are shown in Fig. 1, while the main characteristics of each are shown in Table 1.

Instrumental data is only available for the last two centuries. The monthly (from 1786 onwards) and daily (from 1854 onwards) rainfall series for Barcelona (Barriendos et al., 1997; Barrera-Escoda, 2008) have been updated until the year 2012. Taking into account its location and climate, Barcelona is a good representative for precipitation behaviour along the Catalan coastal region, despite the fact that some flash floods occurred in the city can be due to only local rainfall that can miss the city or rainfall in Barcelona missing other catchments. This series is the longest set of instrumental data available for rainfall in the western Mediterranean. A representative annual mean average areal precipitation series for the North-Eastern Iberian Peninsula (NEIP), with records for over 100 years, has been also used to complete the analysis. This areal precipitation series has been computed from all available monthly precipitation series within the NEIP with a continuous temporal record greater than 90 years (Barrera and Llasat, 2004).

A seasonal reconstruction (1500-2000) for the North Atlantic Oscillation (NAO) developed by Luterbacher et al. (2002) was used in order to analyse the relationship between floods and general circulation. The NAO is a large-scale seesaw in atmospheric mass between the subtropical high and the polar low. It is also the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and covering much of Northern Asia, although it has an impact on every season. Therefore, it is a good indicator for general circulation in Europe (Hurrell et al., 2003).

Finally, solar activity is taken into account using annually resolved ^{10}Be measurements for the past 600 years (1389-1994) taken from the North Greenland Ice Sheet Project (NGRIP) 1997 S2 ice core (Berggren et al., 2009). This data is used to study the possible relationship with flood frequency. It is currently the only available series for annually resolved solar activity and covers almost the same period as the flood data.

3 Methodology

The criterion for flood classification (Barriendos et al., 2003; Llasat et al., 2005) is as follows:

- Ordinary or small floods (ORD): do not cause rivers to overflow their banks, cause some damage if activities are being carried out in or near the river at the time, and cause minor damage to hydraulic installations.

- Extraordinary or intermediate floods (EXT): cause the overtopping of riverbanks, inconveniences in the daily life of the local population, and damage to structures near the river or torrent with possible partial destruction.

- Catastrophic or large floods (CAT): cause the overtopping of riverbanks and lead to serious damage to or destruction of hydraulic installations, infrastructures, paths and roadways, buildings, livestock, crops, and so on.

This classification allows us to compare historic floods and those that were documented with instrumental records. It also matches similar criteria or methodologies used in other European countries such as in the study by Sturm et al. (2001), Glaser et al. (2010) or Petrucci et al. (2012). This kind of classification refers to the flood as a risk, including all the factors that could be involved in the produced impact (hazard, vulnerability, exposure, emergency management...). Consequently, the change in anyone of these factors may affect the evolution of risk and impact.

For each type of flood and location, a flood frequency index has been compiled to show the annual scale. Ordinary floods have not been considered due to overall heterogeneity (most of them were not recorded throughout history). Each flood series is normalised by taking into account the annual-mean value and standard deviation of flood occurrence for the 1901-2000 period as follows:

$$x = (n - m) / s \qquad (1)$$

where n is the yearly flood occurrence; m is the annual-mean value; and s is the standard deviation. This procedure has also been applied in Barriendos et al. (2003) where the homogeneity of the series were analysed following the methodology proposed by Lang et al. (1999). On the other hand, this normalisation is necessary in order to cope with different data series and to construct a geographically representative series. Finally, in order to show the changes in the flood indices clearly, all the values are smoothed by low-pass Gaussian filters of 11 and 31 years (Llasat et al., 2005, Barrera et al., 2006). A representative flood index for each category and for Catalonia as a whole has been developed by averaging out the normalised flood series.

Temporal trends are calculated using the flood index series (not smoothed) by means of a linear regression testing its significance level following a Monte Carlo method (Lizevey and Chen, 1983). This technique consists in the following steps: 1) Calculation of the linear trend of the original series by the linear fitting of data (minimum squares or linear regression). 2) Generation of 10,000 random permutations of the original series. 3) Calculation of the linear trends for each 10,000 generated series. 4) Calculation of the 97.5 and 2.5 percentiles for the 10,000 calculated linear trends. 5) Finally, if the first linear trend calculated was higher(lower) than 97.5(2.5) percentile for its positive(negative) value then, the obtained trend would be significant at 95%. Temporal correlations are calculated using Pearson's linear coefficient, and are applied to the raw data without being smoothed. Spectral analysis is carried out by means of Tukey's power spectrum with a confidence level of 95%, computed using unsmoothed data. The anomalous periods are those with a high frequency in flood occurrence, which are estimated from the mean value plus the standard deviation of a temporal series. In this work, they have been obtained only for catastrophic floods which are the most related to climatic factors. The catastrophic flood series have been smoothed using a low-pass Gaussian filter of 31 years like in other studies (i.e. Llasat et al., 2005; Glaser et al., 2010), and the threshold to consider an anomalous period is defined by flood indexes greater than or equal to 0.1 (mean value + standard deviation ~ 0.1).

4 Results and discussions

4.1 Flood variability

Seasonal flood distribution shows that autumn is the season with the greatest number of floods (54%), followed by summer (21%), with the highest number in October (21%), followed by September (20%) (Fig.2). Catastrophic floods are mainly concentrated between September and November, while August also records a high frequency of extraordinary floods (23% of catastrophic floods are recorded during the summer). These summer events are usually associated with coastal flash-floods produced in short, torrential watercourses, which cause extraordinary damage (Llasat et al., 2013). Barcelona is a good example, with a flood percentage of 29% during the summer.

The temporal evolution of the annual catastrophic flood index for Catalonia (Fig. 3a) shows a greater inter-annual variability up until the 19th century than for the last century alone (σ=0.26 vs. σ=0.22). This evolution also shows different periods of high and low catastrophic flood frequency. The periods with the lowest frequency of catastrophic floods are the mid-14th and mid-17th century, the beginning of the 18th century and the end of the 20th century and beginning of the 21st century. On the other hand, seven different anomalous periods of high flood frequency are highlighted in Fig. 3a: 1) 1325-1334 (Late Middle Age Oscillation), 2) 1541-1552 (Mid-16th century Oscillation, Brázdil et al., 1999), 3) 1591-1623 (Beginning of Little Ice Age Oscillation, LIA, Jones et al., 2001), 4) 1725-1729 (what we propose calling the "Enlightened" Oscillation), 5) 1761-1790 ("Maldà" Oscillation, Barriendos and Llasat, 2003), 6) 1833-1871 (End of LIA, Llasat et al., 2005), and finally 7) 1895-1910 (what we propose calling the "Modernist" Oscillation). Similar anomalous periods were found in other flood series for Central Europe (Glaser and Stangl, 2004), Southern France (Lang et al., 2000; Lang and Cœur, 2002) and Northern Italy (Camuffo and Enzi, 1996), especially the 3rd, 5th and 6th oscillations. Most recently, Glaser et al. (2010) have identified four common anomalous periods of high flood frequency for Central and Eastern Europe: 1540-1600, 1640-1700, 1730-1790 and 1790-1840, which match to a certain extent with the 2nd, 3rd, 4th, 5th and 6th oscillations found in Catalonia. However, most catastrophic floods produced in Central and Eastern Europe are due to thawing in spring after anomalous high accumulation of ice jam combined with abundant rainfalls. This is not the usual case for Catalonia, but periods with a high frequency of catastrophic floods in both zones are as a result of climate anomalies affecting the whole continent.

Trend analysis of temporal evolution for flood indices in Catalonia shows that catastrophic floods do not present a statistically significant trend, whereas extraordinary floods have seen a significant increase, especially from 1850 to the last decades of the 20th century (Fig. 3b). Extraordinary floods are responsible for the total increase in flooding in Catalonia (Fig 3c). Due to the diversity of the catchments studied in this paper, we have separated them into inland basins (Ebro, Segre and Ter catchments) and coastal basins (Llobregat estuary, and the Barcelona and Maresme regions) for a more in-depth analysis. This means Fig. 4 shows how small and torrential coastal basins have seen a significant increase in flood frequency (+0.11/100yr), which is two times or more the magnitude of those in inland basins. Thus, coastal basins are mainly responsible for the increase in flood frequency, especially for extraordinary floods (+0.08/100yr). In particular, the detailed analysis of urban floods in the city of Barcelona from 1351 onwards shows a significant trend (+0.26/100yr) that is mainly due to the increase in extraordinary floods in the summer (+0.13/100yr). This trend could be due to the strong flood occurrence increase in the middle of the 19th century (Fig. 5), which could either be related to the end of the LIA (in the case of France see Lang et al., 2002) and a possible corresponding increase in convective precipitation, or the notable urban changes in the city. The expansion of the city to the river flanks, but especially the demolition of the walls that frequently acted as flood protection barriers, increased the flood vulnerability and exposure in the new and old city during a period of increasing frequency of high rainfall events (Llasat et al., 2005; Barrera et al., 2006). However, the construction of the drainage network and the coverage of the wadis in the late 19th century and early 20th century decreased again the vulnerability (Martín-Pascual, 2009).

The large reservoirs built to generate electricity and supply water for agriculture in the main drainage basins in Catalonia during the second half of the 20th century (between the 1960s and 1970s) have probably lessened the flood hazards in the Inland Basins, producing less catastrophic floods and a slight increase of extraordinary ones as it is shown in Fig. 4. Elements such as further mitigation measures, changes in land use, exposed assets and climatic factors should be also considered. A larger population living in flood-prone areas and exposed assets in coastal regions could be one of the key factors responsible for the rise in extraordinary floods in the region.

Spectral analysis applied to the annual catastrophic flood index series for Catalonia shows two main significant periodicities (Fig. 6) of 71 and 2.6 years. The first could be related to the Gleissberg solar cycle (~70-100 yr) and the second to the Quasi-Biennial Oscillation (QBO ~28-29 months ~2.33-2.42 yr), which is present in almost all temporal series involving climatological and meteorological variables (Baldwin et al., 2001). Two less significant periodicities of 4.2 and 2.2 years are also shown, which could be also associated with the QBO.

4.2 Floods versus rainfall

Autumn precipitation contributes less to annual precipitation than autumn floods contribute to the annual total, but it is nonetheless the rainiest season in most of Catalonia. In Barcelona for example, autumn precipitation represents 37% of annual precipitation, followed by spring (25%), for the period 1786-2012. Summer is the driest season, contributing to just 18% of total annual precipitation in Barcelona. However, summer precipitation is mainly convective (nearly 65% in August, see Llasat, 2001), and is usually associated with thunderstorms or localised heavy rain that produces flash floods in coastal water streams.

On an annual scale, the temporal evolution of precipitation anomalies in Barcelona since 1786 and the same variable for areal precipitation in the NEIP do not show any significant long-term trends (Fig. 7). These same findings are shown for changes to annual maximum daily precipitation in Barcelona (Barrera et al., 2006), and for the number of days that exceed different daily precipitation thresholds (20, 30, 50 and 100 mm in one day; Fig. 8). Subsequently, when considering this common non-significant trend, we can state that annual extreme precipitation has not increased. These results can be extrapolated to the entire Catalan coastal region, although the precipitation series is smaller (Llasat et al., 2009). Similarly, Turco and Llasat (2011) analysed the evolution of extreme precipitation through the ETCCDI (Expert Team on Climate Change Detection and Indices, Zhang et al., 2011), in Catalonia from 1951 to 2003, and did not find any significant increase in total precipitation, neither in the highest precipitation amount in a five-day period (RX5DAY), or in the mean precipitation amount on a wet day (SDII) or in the proportion of heavy rainfall (R95p). Working on a seasonal scale and focusing on the city of Barcelona, some trends are shown if the confidence level is reduced to 90%. In this case, a positive trend of +0.12 mm/yr can be found for summer precipitation in the city, which corresponds to a certain extent with the increase in extraordinary floods in the summer (Fig. 5). These results match the increase in precipitation in August in the city, with a significant value of +2.73 mm/yr for the 1850-1984 period, as shown by Altava-Ortiz et al. (2010).

The correlation between annual precipitation and the annual index for different types of floods (1786-2012) is very low and changes over time. The 31-year moving correlations between annual precipitation and catastrophic floods in Barcelona (Fig. 7a) show a maximum value (r=+0.59) for 1860-1890 related to the end of the LIA (characterised by very wet years and without flood protection measures). From 1957 on, there is null correlation, maybe as a result of different hydraulic works developed within the city to diminish flood risk and less climatic variability (Barrera et al., 2006; Martín-Pascual, 2009).

In Barcelona, the temporal correlation (Fig. 8) between total annual floods and the number of days exceeding thresholds of 20 mm/d, 30 mm/d, 50 mm/d and 100 mm/d is relatively low for the 1854-2012 period, which shows the most significant correlation for the number of days exceeding 50 mm (+0.24). The correlation between the previous thresholds and the catastrophic flood index also shows the same pattern. Barrera et al. (2006) outlined that urban growth in the city of Barcelona has had an impact on flood vulnerability and the flood frequency from the 14th century onwards, especially from the late 19th and early 20th century. This fact is corroborated when analysing the 31-year moving correlations for the above-mentioned variables for raw data (Fig. 8). Considering the total annual number of floods and number of days above 50 mm/d they reached values above +0.60 for 1936-1985, which could be considered as an homogenous period because the city drainage system did not experience significant changes (Martín-Pascual, 2009). The construction of water tanks, from 1990s on, diminished the correlation with the 50-mm threshold and improved the one with the 100-mm threshold arriving to +0.61. On the contrary, after the wall demolition and initial urban occupation of flood-prone areas, the 20-mm threshold shows the best correlations. This fact corroborates the strong sensitivity of rainfall threshold associated with floods to changes in vulnerability.

As a result, rainfall patterns alone cannot explain the changes in floods in the region. Extraordinary floods are more frequently related to flood vulnerability and land-use, while catastrophic floods are associated with climatic factors.

4.3 Climatic factors

4.3.1 General Circulation

While there is no single atmospheric synoptic pattern associated with floods in Catalonia, the analysis of recent and past floods suggests a predominant southern circulation for autumn floods. This implies a relation with a negative NAO phase (Trigo et al., 2004; Llasat et al., 2005), while summer events would be more closely associated with northern circulation in low levels in the region, with a meso-low in eastern Catalonia. In this latter instance the NAO phase would be more likely to be positive when taking into account the position of the Azores Anticyclone during the summer. However, the correlation between NAO and precipitation in the Mediterranean region for the summer season is very low and not significant, due to the important role of local convective developments. For this reason, it does not make sense to analyse the potential relationship between NAO and summer floods.

Following the previous discussion, the influence of general circulation on catastrophic floods in Catalonia has only been analysed for the autumn season (accounting for 55% of all catastrophic floods, see Fig. 2), by means of the NAO reconstruction set out by Luterbacher et al. (2002) for 1500-2000 (Fig 9). The temporal correlation between these variables is fairly low with a significant value of +0.09. The low level of correlation is not unusual because some floods are isolated local events produced by short heavy rainfall that can take place under positive or negative NAO phases, depending more on mesoscale features than synoptic patterns. Besides this, the frequency of flood events is extremely low, and this affects the significance of any potential correlation. Seasonal shifts in flood distribution could also be produced as a consequence of changes in atmospheric conditions and their effect in precipitation features and snowmelt. On the other hand, the relationship between the NAO and precipitation has changed over time for the 20th century (Knippertz et al., 2003; Trigo et al., 2004; Beranová and Huth, 2008). For the last 500 years, the temporal evolution of the 31-year moving correlations between floods and NAO (Fig. 9) also show a similar behaviour with a high variability. The highest correlations were found during the central part of the LIA: a maximum value of +0.54 for 1673-1703 and a minimum value of −0.35 for 1618-1648; both periods with low flood frequency. The most important peak in floods was at the beginning of the LIA, a period with the minimum NAO values. The end of the LIA, this so called "Modernist" Oscillation and the 1970s-1980s also correspond to a negative NAO phase. On the contrary, the "Maldà" Oscillation was a special period with both floods and droughts, mainly associated with a great NAO variability (but with a predominance of positive values). A major occurrence of unusual winter thunderstorms and heavy rainfalls related to zonal circulation could explain this anomalous period at annual scale (Barriendos and Llasat, 2003). Finally, some periods of relatively high flood frequency occur within periods of strong changes to the NAO.

4.3.2 Solar variability

As previously mentioned, the most significant oscillations are shown in different basins in Europe and are correlated with the main phases of the LIA (Camuffo and Enzi, 1996; Brázdil et al., 1999; Pfister, 1999; Benito et al., 2003; Llasat et al., 2005; Glaser et al., 2010). The first oscillation (LMA) was produced at the end of Wolf Minimum, while the second one (m16) corresponded to the end of Spörer Minimum (Fig. 3a). On the contrary, the most significant period of high flood frequency (bLIA) was recorded near maximum solar activity levels that started in 1580 at the beginning of the LIA, and during the Maunder Minimum flooding activity decreased (Fig. 3a). The Wolf, Spörer and Maunder are considered the last "grand minima" (Usoskin et al., 2007), for which sunspot activity decreased considerably more than for the other minima. The first half of Dalton Minimum coincided with the Maldà Oscillation, which was characterised by high climatic irregularity accompanied by hydrologic extremes. The maximum period of flood frequency for the end of the LIA (eLIA) corresponds with the highest levels of solar activity recorded between 1849 and 1875. Summarising, flood-rich periods are only related to maximum solar activity at the beginning and end of the LIA.

In Central Europe (Brázdil et al., 1999), the periods with the most flooding were recorded in the mid-16th century and in the late Maunder Minimum (1675-1715), corresponding to periods with less solar activity. On the contrary, Vaquero (2004), from a visual inspection, points to a major flood frequency in Tagus River (Iberian Peninsula) associated with maxima solar activity. This suggests that the regional component is very important. This fact is not strange if we consider the different circulation patterns associated with heavy rainfalls and floods (including snowmelt) and their potential seasonal shift for different periods. Other authors (Borgmark, 2005; Versteegh, 2005; Wilhelm et al., 2012) also attribute the periodicities found in many geological flood records to extraterrestrial forcings, such as centennial and decadal solar cycles.

Fig. 10a shows a comparison of the annual evolution in solar activity (1389-1994) taken from the ^{10}Be concentration and the catastrophic flood index series for Catalonia (1301-2012). ^{10}Be concentration is high for periods of low solar activity and low for periods of high solar activity. The temporal correlation between raw data is extremely low ($r=-0.06$), but its long-term correlation (with 31-year filtered data) arrive to $r=-0.33$. This last value implies that lower ^{10}Be concentration (greater solar activity) would be related to periods with higher flooding activity. However, the 31-year moving correlations between them have changed over the time and shown a great variability, with a minimum value of −0.34 for 1600-1630 (period with a high solar activity and the maximum flood frequency) and a maximum value of +0.37 for 1726-1756 (period with significant increase in solar activity and decrease in flood frequency). Then, the most flood-rich period recorded at the beginning of LIA period, would be related with a maximum of solar activity and strongly negative NAO values. On the contrary, visual inspection shows that secondary flood peaks could be related with the Wolf, Spörer and Dalton Minima, mainly characterised by positive NAO values (Fig. 9). If the analysis focuses solely on autumn (SON; Fig. 10b), the temporal correlation between solar activity and floods is higher, reaching values of −0.08 for raw data and −0.42 for smoothed data. The related 31-year moving correlations also show higher correlations with a minimum value of −0.38 for 1616-1646 and a maximum value of +0.62 for 1726-1756. Finally, it is also interesting to note that a significant change in flood occurrence could be associated with transient periods between solar maxima and minima, and periods of solar maximum (Fig. 10). In addition to this observation, we should mention that the reconstruction of solar activity from ^{10}Be concentration does not give the exact dates of the maxima due to dating uncertainties and the length of periods of minimum solar activity are not strictly delimitated (Berggren et al., 2009).

The possible link between floods and solar activity is somewhat controversial (Benito et al., 2004; Vaquero 2004). If we consider the accepted hypothesis that flood-producing mechanisms in the past are similar to those in the present, then marked clusters of historical floods could be associated with changes to the climatic pattern on both a regional and global scale, and, in turn, to changes in solar activity. Although this potential relationship is still a challenge for the scientific community and merits further research, some studies have revealed the influence of solar activity in North Atlantic atmospheric and ocean circulations (Moffa-Sánchez et al., 2014). Following on from this, solar activity would have an impact on the development and trajectory of Atlantic perturbations that could arrive to Europe; low solar irradiance would promote the development of frequent and persistent atmospheric blocking events, with a quasi-stationary high-pressure system in the eastern North Atlantic, which would modify the flow of westerly winds. This kind of pattern could be identified by a positive NAO phase, and would make it more difficult for low-pressure systems and the associated perturbations to arrive in southern Europe. On the other hand, this would favour their arrival in central and northern Europe. Given that floods produced by heavy rainfall are associated with different circulation patterns, the effect of solar variability could change from one region to another. These explanations are coherent with our previous results that correlate positive (negative) NAO with minimum (maximum) solar activity.

Furthermore, maximum solar activity is associated with low intensity cosmic rays in the stratosphere, which results in greater ozone production in some regions and subsequent warming (Ermolli et al., 2013). Besides the influence of solar activity on general circulation and winds, this differential warming of the stratosphere might influence the development of potential vorticity and the dynamics near the tropopause. Therefore, it could have an important role in heavy rainfall.

5 Conclusions and discussion

The analysis of a reviewed flood index series for the north-eastern Iberian Peninsula (1301-2012) shows that catastrophic floods (the most severe ones) are mainly concentrated in the autumn, while extraordinary floods (moderate ones) generally occur in the late summer and early autumn. These results corroborate those obtained for other shorter periods in Catalonia (i.e. Llasat et al., 2014), the similarities with South of France, and the differences with the Central Mediterranean region where maximum flood frequency is recorded in winter (i.e. Llasat et al., 2013). This distribution is coherent with the bimodal precipitation distribution in Catalonia, with a principal maximum in autumn, usually related to convective events; while the secondary one recorded in spring proceeds from usually stratiform events with not very high intensities (Jansà, 1997; Llasat et al., 2007). On the contrary, summer is characterised by the contribution of convective precipitation to total precipitation, usually caused by thunderstorms or local heavy rainfall giving way to flash floods (Llasat, 2001).

Trend analysis does not show any notable trends for catastrophic floods, although there is a statistically significant trend for extraordinary floods, which implies that a significant increase in the total number of floods has been found since the 14th century. This increase is mainly associated with the extraordinary floods recorded in small and torrential basins located near the coast This trend is exacerbated in the case of urban floods in Barcelona since 1351 and it can be explained by the strong flood increase that occurred in the mid-19th century, which is probably rooted in both climatic (a slight trend in summer precipitation has been found) and human causes (walls destruction, urban development, etc). Notwithstanding, the increase in extraordinary floods in small coastal basins is mainly related to the marked increase in developed land over the last century, and especially over the last 30 years, which implies a significant change in flood vulnerability and land use, as was recently stated by the IPCC (2012). On the contrary, the evolution of daily rainfall thresholds associated with urban floods in Barcelona corroborates the positive role of prevention measures, such as the improvement of the drainage system including pluvial tanks or the early warning systems. In effect, this threshold has evolved from 20 mm for the late 19th and early 20th centuries, to 50 mm for almost the 20th century and 100 mm from 1990s on. These results point to the necessity of considering floods from a holistic point of view, and support the remarks from IPCC (2012) or the recent review paper from Hall et al. (2014).

The temporal evolution shows seven different anomalous periods of high catastrophic flood for Catalonia: 1) 1325-1334 (Late Middle Age Oscillation), 2) 1541-1552 (Mid-16th century Oscillation), 3) 1591-1623 (Beginning of LIA), 4) 1725-1729 (what we propose calling the "Enlightened" Oscillation), 5) 1761-1790 ("Maldà" Oscillation), 6) 1833-1871 (End of LIA), and finally 7) 1895-1910 (what we propose calling the "Modernist" Oscillation). The anomalous periods 2, 3, 5 and 6 coincide totally or partially with those common periods with high flood frequency for Central and Eastern Europe identified by Glaser et al. (2010). This fact points to search for climatic causes that would affect northern atmospheric circulation pattern.

Attending to the fact that extraordinary floods can be seriously affected by no climatic factors, only the correlation between catastrophic floods and the NAO and solar variability has been analysed. Results have shown that the correlation with the NAO for autumn changes over time: in the second half of the 17th century it reaches +0.54 while in its first half of the same century it reaches just −0.35, both periods with low flood frequency. This is not unusual in itself, given that the present correlation between the NAO and precipitation in this specific region and season does not reach −0.50 (Barrera and Llasat, 2004; Martín-Vide and López-Bustins, 2006). The detailed analysis for the entire Spain in the last 100 years also shows how negative correlation has increased in the last few decades (Barrera-Escoda, 2008). This complex relationship between the NAO and flooding has been also found for Britain (McDonald, 2014). However, the most significant flood oscillations occur at the beginning and end of the LIA, and this so-called "Modernist" oscillation coincides with a strong negative NAO phase, as for the last anomalous period in the 20th century.

Spectral analysis shows two key periodicities for the annual catastrophic flood index. The first one (71 yr) could be related to the Gleissberg solar cycle, and the second one (2.6 yr) to the Quasi-Biennial Oscillation. Although the possible links between floods and solar activity are still controversial, the correlation between ^{10}Be concentration (maximum when solar activity reaches a minimum) and the catastrophic floods may provide some interesting information. Until the moment approaches to this issue have been mainly qualitative (i.e. Vaquero, 2004). This correlation shows a significant value of −0.33 (−0.42 if only the autumn season is taken into consideration) and points to the fact that major solar activity is usually associated with periods of higher flooding activity. This is particularly important at the beginning and end of the LIA, and corroborates the positive significant relationship between solar magnetic activity and floods in the UK (MacDonald, 2014). Significant changes in flood occurrence could be associated with transient periods between solar maxima and minima. Recent studies (Martín-Puertas et al., 2012; Moffa-Sánchez et al., 2014) have revealed the possible influence of solar activity through changes to solar irradiance (mainly in the ultraviolet) and changes in cosmic rays and solar particles as they arrive in the stratosphere. Although these studies mainly refer to winter-early spring North Atlantic circulation (both atmospheric and ocean circulations), and floods in Catalonia are mainly produced in autumn, they provide a departure point for future research on this possible "top-down" mechanism. Changes in solar irradiance over the North Atlantic would be amplified through atmospheric feedbacks including the Atlantic Meridional Overturning Circulation, which would in turn affect the formation of persistent atmospheric blocking events. The latter factor would also affect the predominant circulation patterns (i.e. NAO), with the consequent differential regional influence for heavy precipitation. Less interaction between cosmic rays and the ozone in the stratosphere during periods of maximum solar activity would increase ozone presence, diminish UV radiation arriving on the Earth surface, and increase the stratospheric temperature in some regions, with a consequent impact on the dynamics of the high atmosphere.

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Table 1. Main characteristics of the updated flood chronologies: basins, locations, sub-basin surface at the location, temporal coverage and the number of extraordinary (EXT), catastrophic (CAT) and total (TOT=EXT+CAT) floods.

Basin	Location	Surface (km^2)	Period	EXT	CAT	TOT
Segre	la Seu d'Urgell	1,233	1451-2012	16	19	35
	Balaguer	7,796	1616-2012	9	14	23
	Lleida	11,389	1301-2012	24	27	51
	TOTAL	12,879				
Ebro	Tortosa	82,763	1351-2012	34	15	49
	TOTAL	83,093				
Llobregat	Martorell	4,561	1301-2012	98	25	123
	TOTAL	4,957				
Ter	Camprodon	280	1616-2012	6	4	10
	Ripoll	738	1576-2012	10	7	17
	Girona	1,802	1301-2012	112	22	134
	TOTAL	3,010				
Maresme	Calella	10	1671-2012	31	15	46
	Arenys de Mar	28	1666-2012	59	35	94
	Mataró	22	1739-2012	78	39	117
	TOTAL	342				
Pla de Barcelona	Barcelona	100	1351-2012	157	43	200

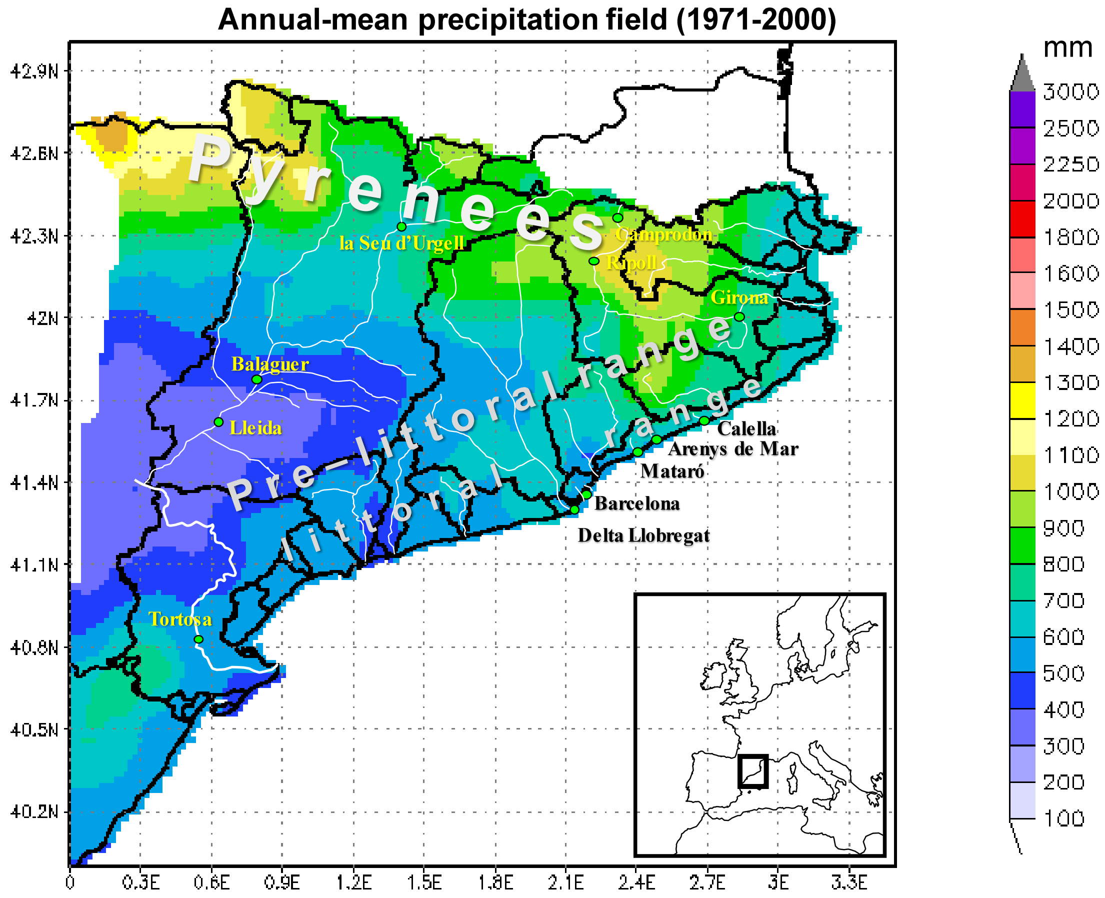


Figure 1. Annual-mean precipitation field for Catalonia (1971-2000) at 5-km resolution and computed from a high-density network of observations (Adapted from Altava-Ortiz, 2010). The three main mountain ranges of Catalonia are shown over the map. The Catalan river basins and their related main water courses are also displayed. Finally, the location of the analysed flood chronologies is also shown.

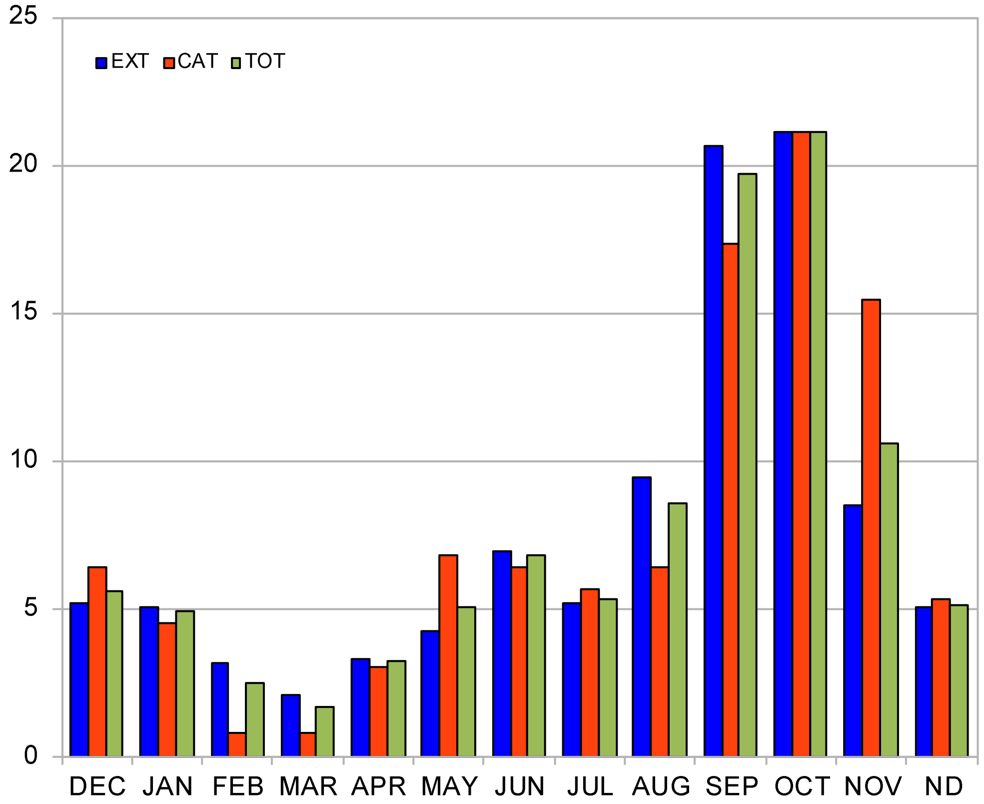
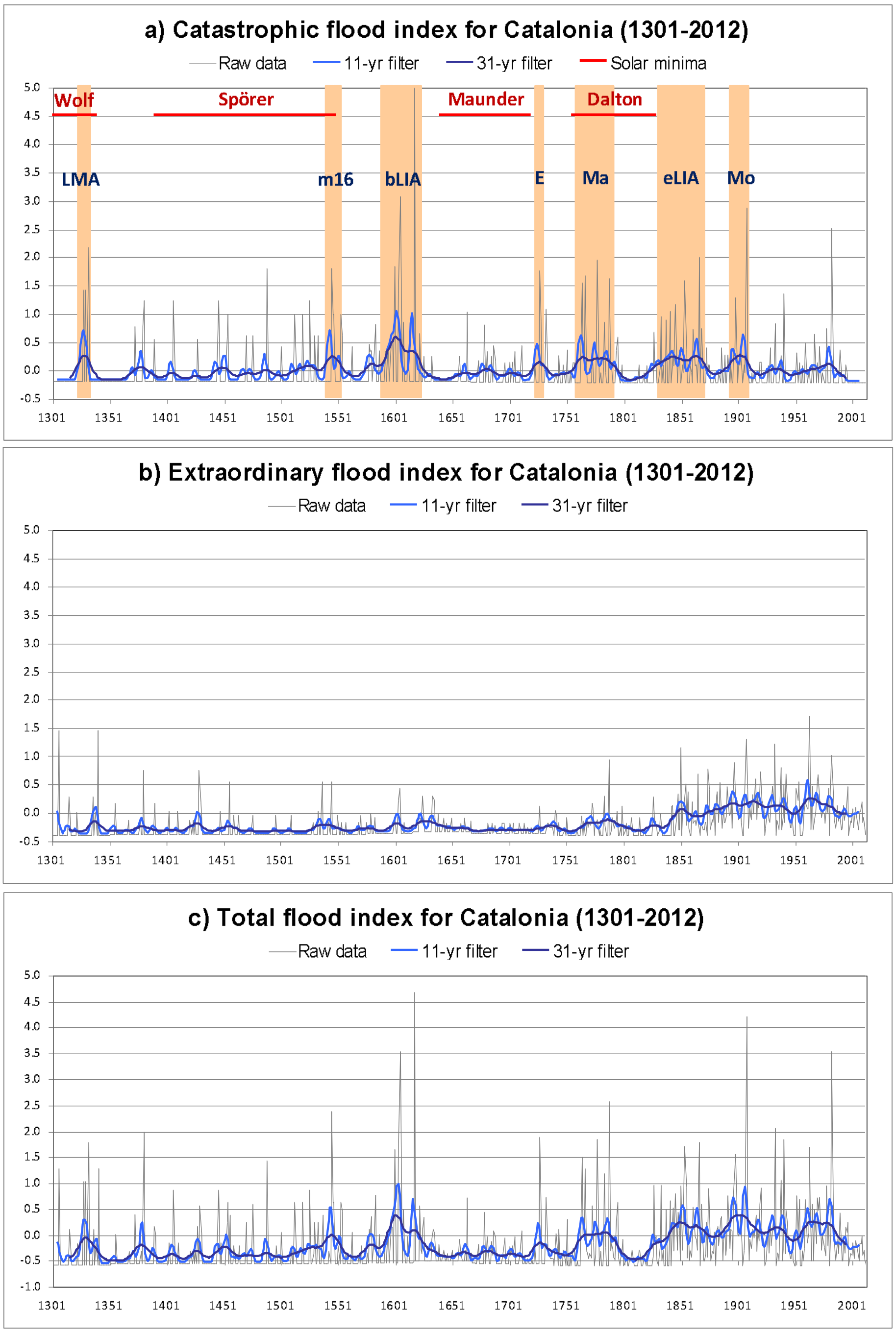


Figure 2. Temporal distribution of historical floods in Catalonia (1301-2012). Extraordinary (EXT), catastrophic (CAT) and total (TOT=EXT+CAT) floods. ND indicates floods with an unknown exact date.


a) Catastrophic flood index for Catalonia (1301-2012)

b) Extraordinary flood index for Catalonia (1301-2012)

c) Total flood index for Catalonia (1301-2012)

Figure 3. Temporal evolution of catastrophic (a), extraordinary (b) and total (c) flood index series for Catalonia (1301-2012). Data smoothed by low-pass Gaussian filters of 31 and 11 years are also displayed. Anomalous periods of high catastrophic flood frequency and periods of solar minimum (following Usoskin et al., 2007) are highlighted in figure a: LMA (Late Middle Age Oscillation), m16 (Mid-16th century Osc.), bLIA (Beginning of LIA Osc.), E ("Enlightened" Osc.), Ma (Maldà Osc.), eLIA (End of LIA Osc.) and Mo ("Modernist" Osc.).

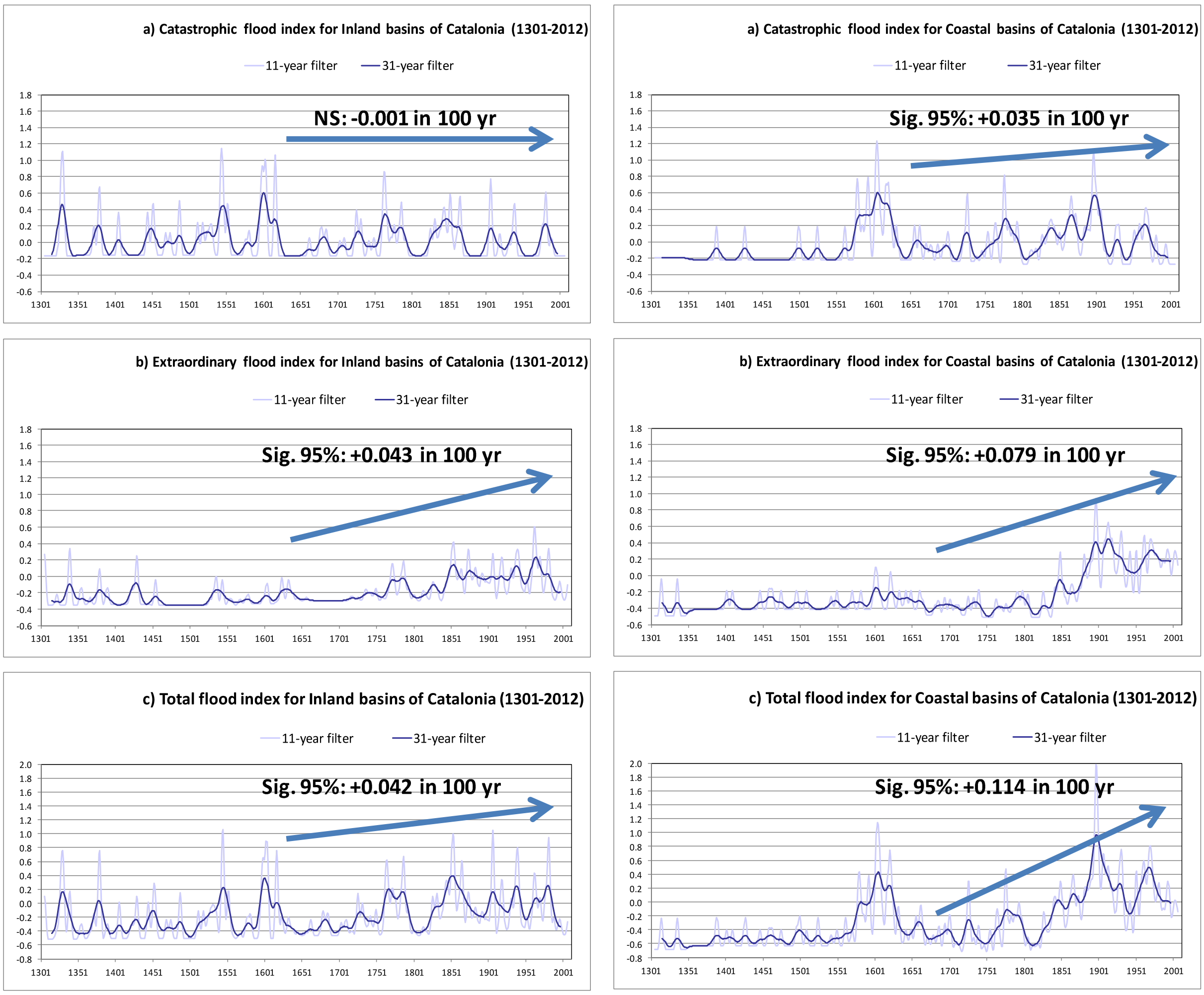
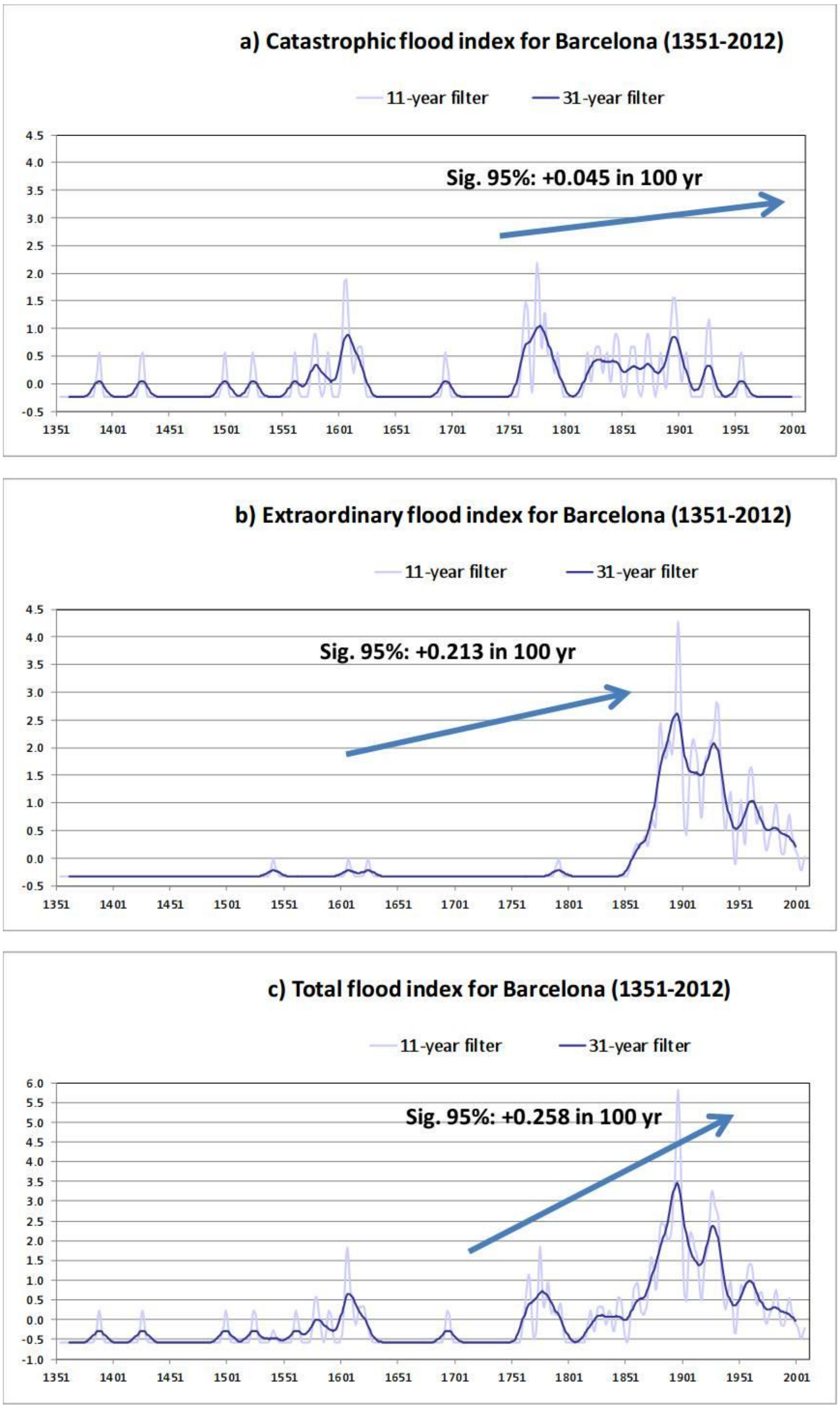


Figure 4. Temporal evolution (1301-2012) of catastrophic (a), extraordinary (b) and total (c) flood index series for inland (Ebro, Segre and Ter basins; left panels) and coastal basins (Llobregat mouth, Barcelona County and Maresme basin; right panels). The result of applying a trend analysis for each series is also shown.


a) Catastrophic flood index for Barcelona (1351-2012)

b) Extraordinary flood index for Barcelona (1351-2012)

c) Total flood index for Barcelona (1351-2012)

Figure 5. Temporal evolution of catastrophic (a), extraordinary (b) and total (c) urban flood index series for Barcelona (1351-2012). Data are smoothed by low-pass Gaussian filters of 31 and 11 years. The result of applying a trend analysis for each series is also shown.

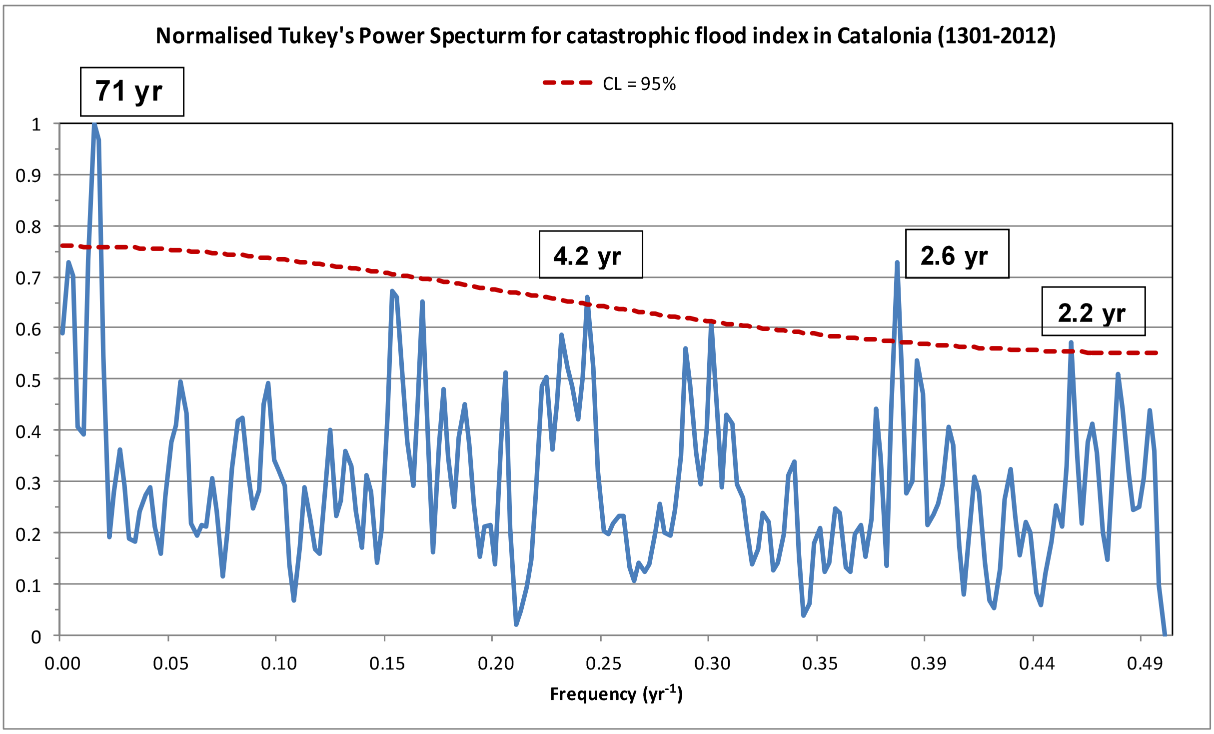


Figure 6. Spectral analysis applied to the catastrophic flood index series for Catalonia (1301-2012) by means of Tukey's power spectrum. The red dashed line represents the 95% confidence level of the spectral analysis applied.

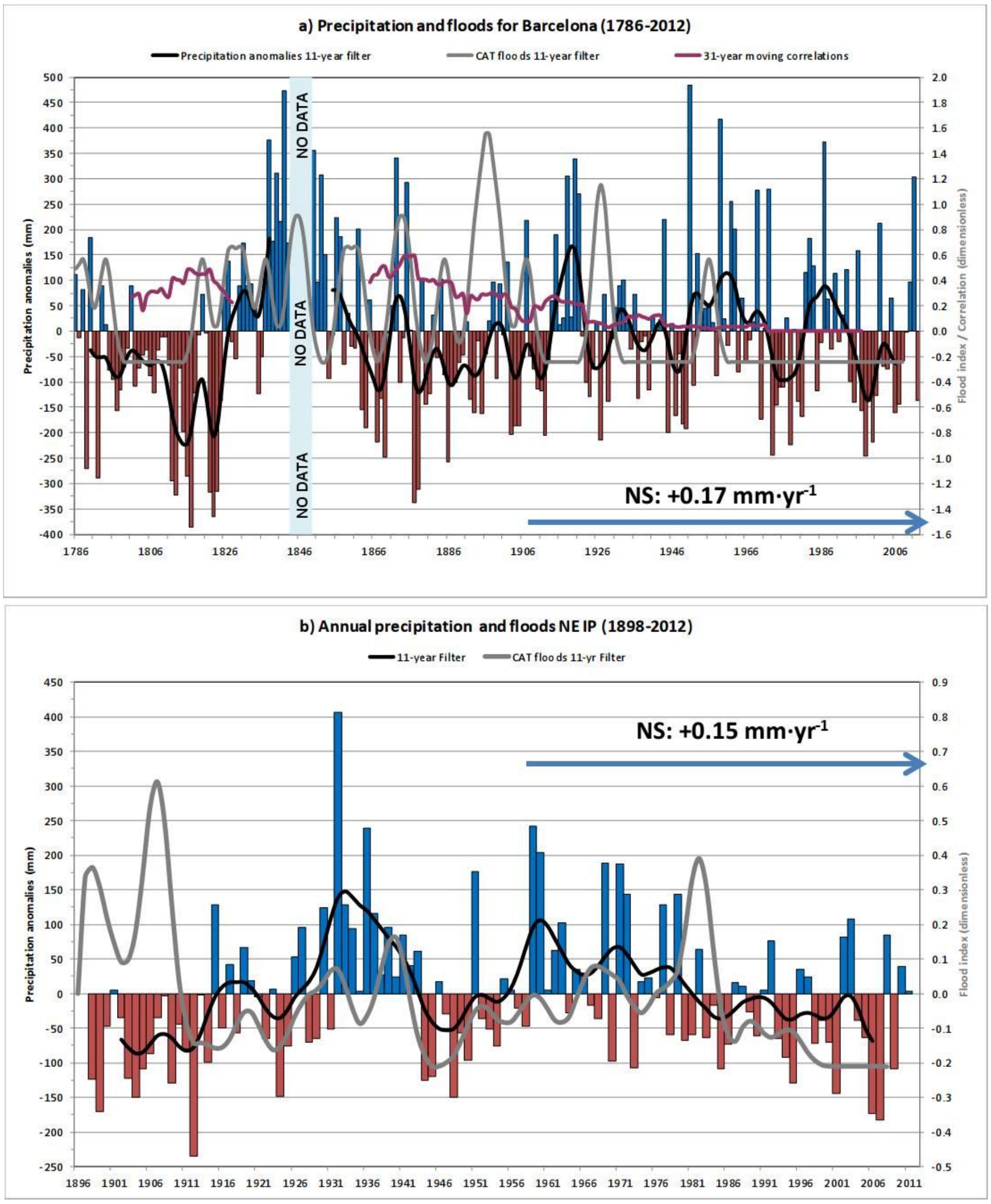


Figure 7. a) Temporal evolution (1786-2012) of annual-mean precipitation anomalies (coloured bars), catastrophic flood index series smoothed by an 11-year low-pass Gaussian filter (grey line) and the 31-year moving correlations between precipitation and catastrophic floods (pink line) for Barcelona. b) Temporal evolution (1898-2012) of annual-mean areal precipitation anomalies (coloured bars) for the North-eastern Iberian Peninsula (NEIP) and catastrophic flood index series smoothed by an 11-year low-pass Gaussian filter (grey line) for Catalonia. In both figures, black lines are the temporal evolution of annual-mean precipitation anomalies smoothed by an 11-year low-pass Gaussian filter. The results of applying a trend analysis in the annual-mean precipitation anomalies are also shown.

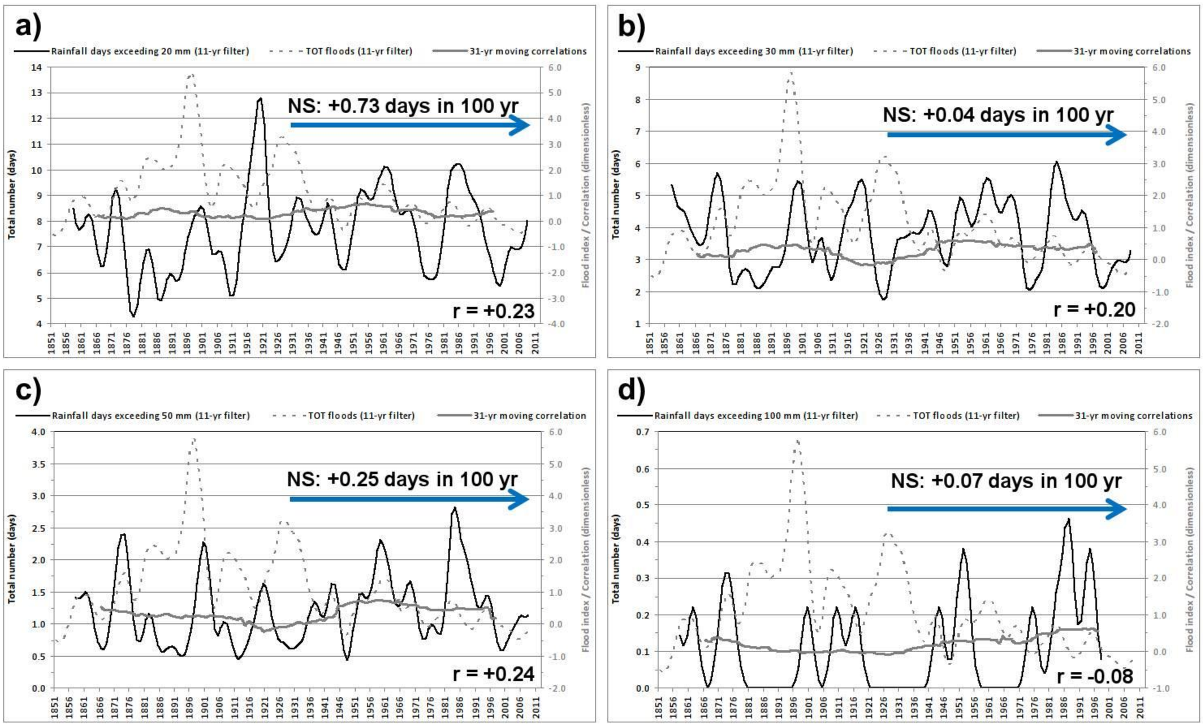


Figure 8. Temporal evolutions of total flood index series and the number of days exceeding a daily precipitation threshold for Barcelona (1854-2012): a) 20 mm, b) 30 mm, c) 50 mm and d) 100 mm. Data have been smoothed by an 11-year Gaussian low-pass filter. The 31-year moving correlations between floods and the different daily precipitation thresholds are also displayed in each panel. The results of applying a trend analysis in the number of days and the temporal correlations between them and floods for all the period are also shown.

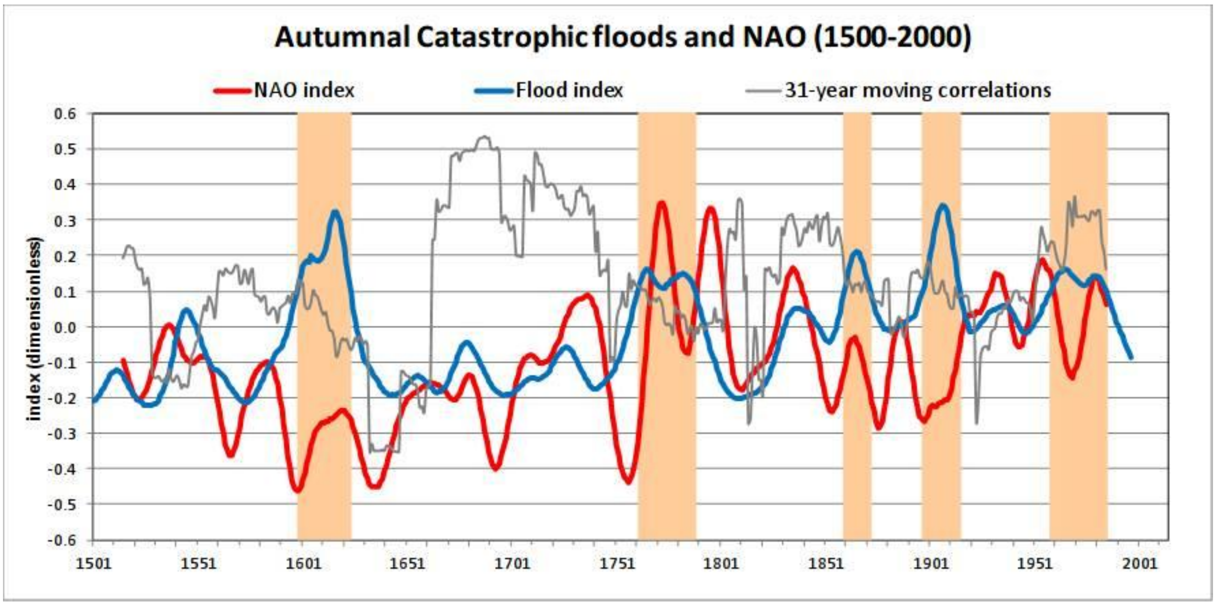


Figure 9. Temporal evolution (1500-2000) of autumnal NAO (Luterbacher et al., 2002; red line), autumnal catastrophic flood index series for Catalonia (blue line) and 31-year moving correlations between both variables (grey line). Data are smoothed by a 31-year low-pass Gaussian filter. The anomalous periods of high flood frequency are highlighted.

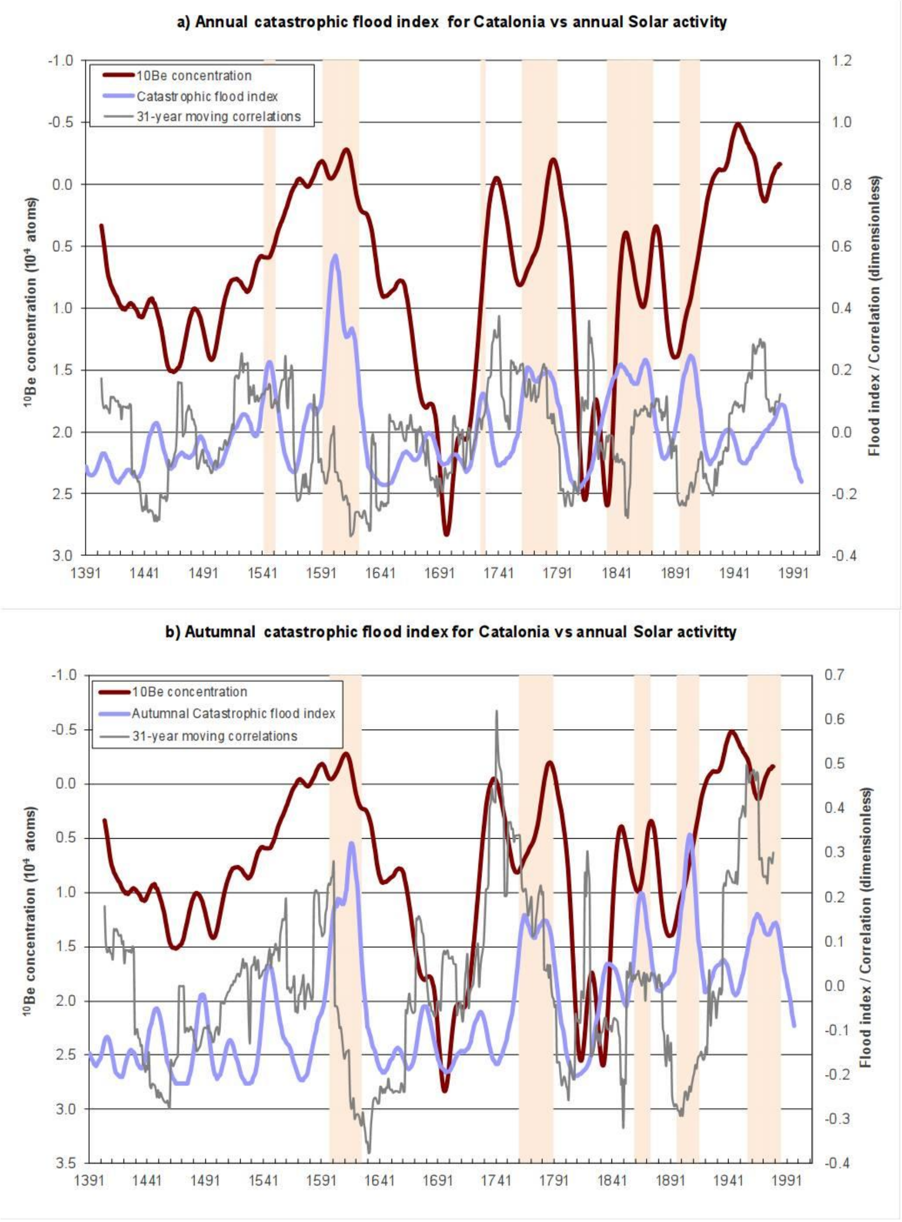


Figure 10. Temporal evolution (1389-2012) of solar activity taken from ^{10}Be (Berggren et al., 2009; brown lines) versus annual (a) and autumnal (b) catastrophic flood index series for Catalonia (blue lines). The temporal evolution of the 31-year moving correlations between solar activity and floods are also displayed (grey lines). Solar activity and flood data are smoothed by a 31-year low-pass Gaussian filter. The scale for ^{10}Be concentration is inverted because its concentration is high for periods of minimum solar activity, and low for periods of maximum solar activity. The anomalous periods of high flood frequency are highlighted in both figures.