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Extreme pointer years in tree-ring records of Central Spain as evidence of volcanic eruptions (Huaynaputina, Peru, 1600 AC) and other climatic events

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Abstract

The study of pointer years based on the numerous tree-ring chronologies of the central Iberian Peninsula (Sierra de Guadarrama) could provide complementary information about climate variability over the last 405 years. In total, 64 pointer years have been identified: 30 negative (representing minimum growths) and 34 positive (representing maximum growths), the most significant of these being 1601, 1963 and 1996 for the negative ones, and 1734 and 1737 for the positive ones. Given that summer precipitation has been the most incident factor in the general variability of growth of *Pinus* in the Sierra de Guadarrama in the second half of the 20th century, it is also an explanatory factor in almost 50 % of the extreme growths. Furthermore, the data show that there has been variability over the centuries in the distribution of the frequencies of pointer years and intervals. The first half of the 17th century, together with the second half of the 20th century, constitute the two most notable periods for the frequency of negative pointer years in Central Spain. This variability was sufficiently notable to affirm that, both in the 17th and 20th centuries, the macroclimatic anomalies that affected growth were more frequent and more extreme than in the other two centuries analysed.

The period 1600–1602 is of special significance, being one of the most unfavourable for tree growth in the centre of Spain, with 1601 representing the minimum index in the regional chronology. It is possible to infer that these phenomena are the effect of the eruption of Huaynaputina, which occurred in Peru at the beginning of 1600 AD. This is the first time that the effects of this eruption in the tree-ring records of central and southern Europe have been demonstrated.

1 Introduction

In recent decades a considerable number of studies have been carried out that have analysed the variability in the climate of the Iberian peninsula over the past millennium from numerous points of view. Starting with the pioneering studies of Fontana Tarrats of the indirect registers of climatic events derived from very diverse documentary sources (mostly unpublished) and in many different regions, and which were compiled and summarised by Font Tullot (1988), the range of knowledge deriving from documentary studies of the past climate of the Iberian peninsula has grown considerably (Martín-Vide and Barriendos, 1995; Rodrigo et al., 1999; Barriendos, 1997; Vicente-Serrano and Cuadrat, 2007; Rodrigo and Barriendos, 2008; Domínguez-Castro et al., 2008, 2010). In some cases, the documentary data have been compared with other proxies, basically proceeding for this period from dendroclimatic (Manrique and Fernández-Cancio, 2000; Saz, 2003; Vicente-Serrano and Cuadrat, 2007; Génova, 2009). Unlike what is habitual in many other regions of the Northern Hemisphere, these reconstructions are not very abundant in our country.

Dendroclimatic studies are valuable for examining the time distribution of climate events because the length of tree ring series provides an extended context to assess such changes. One of the features to assess these changes is pointer years: years with markedly wider or narrower tree-ring width compared to neighbouring tree-rings. In general, the study of the relationship between pointer years and climatic factors has represented only a marginal interest in dendrochronology, especially with the growing application of information technology, because this relationship is not easy to define. Nevertheless, in certain cases and using qualitative techniques, it has indeed been demonstrated that the pointer years that present themselves over wide geographical areas tend to be associated with determinate macroclimatic events, such as severe frost, drought or global-scale volcanic events (LaMarche and Hirschboeck, 1984; Scuderi, 1990; Briffa et al., 1998; Knapp et al., 2002; Hantemirov et al., 2004; Neuwirth et al., 2007). Furthermore, pointer years are also used to support the correct dating in historical or archaeological material (Schweingruber, 1990; Schweingruber et al., 1990; Schweingruber, 1996; Querrec et al., 2009; Génova et al., 2011).

The principal aim of this paper is to provide new insight, based on tree rings, into the climate variability of the central Iberian Peninsula (Sierra de Guadarrama) over the last 405 years. Based on the pointer year analysis of 15 chronologies from 253 trees, the paper aims to provide a more robust characterization of drought variability in Spain where precipitation series longer than one century are very rare (Vicente-Serrano, 2006), and to increase the information about extreme climate events.

The interpretation of the pointer years depends on their site in the dendrochronological sequences and on their significance – whether individual, local or regional (Schweingruber et al., 1990) – although at the regional level only the climatic interpretation is possible. The suitability of pointer years for the determination of extreme climatic events has already been demonstrated (Kienast et al., 1987; Schweingruber, 1990; Meyer, 1999; Génova, 2000; Rolland et al., 2000; Neuwirth et al., 2007). Evident climatic interpretations such as severe winter frosts, unusual summer droughts, or excessive cold springs can explain most of the negative pointer years. Other authors have related negative pointer years with macro-climatic events on a global scale, such as volcanic eruptions (LaMarche and Hirschboeck, 1984; Scuderi, 1990; Jones et al., 1995; Briffa et al., 1998; Hantemirov et al., 2004). Conversely, most positive growth responses are caused by a local combination of favourable ecological factors rather than simple extreme events (Rolland et al., 2000). In this context, the analysis set forth in Génova (2000) has been brought up-to-date and completed, with a global evaluation of the pointer years detected in different sites of Central Spain being carried out. The objective has been to develop a pointer year record of regional signification through a thorough analysis that is narrowly-focused but of great reliability.

2 Material and methods

2.1 Sampling sites and chronologies

The Sierra de Guadarrama forms part of the eastern half of the Central System in the centre of the Iberian Peninsula, situated between the Sierras of Gredos and Ayllón. It extends in a southeast–northeast direction, from the Spanish provinces of Madrid in the southeast to Segovia and Ávila in the northeast. This Sierra extends approximately 80 km in length, and its highest peak is the Peñalara, at 2428 m. The rocky substratum is quite varied, with a great deal of granite in the western parts, while in the centre and northeast there is a predominance of rock with a certain degree of metamorphism, such as gneiss. It is one of the most important forested areas of continental Spain, with a clear predominance, especially above 1000 m altitude, and one of the best representations of *Pinus sylvestris* forest. By the end of the 19th and beginning of the 20th centuries, the area was practically deforested, especially on its southerly slopes, due to repeated fires, war and grazing and the large-scale extraction of wood suffered since the Middle Ages. Consequently, the greater part of the pine woods derive from successive reforestation effected from that time on (Bauer, 1980; Rojo and Montero, 1996; Martínez García and Costa, 2001). Nevertheless, the northern slopes still preserve some of the finest natural Scots pine forests that exist in Spain. The Valsaín forest in Segovia, for example, is one of the few state-owned forests in Spain, and has been managed since the 18th century. Since then it has been drawn upon as a source of timber without interruption until the present day, and has been kept in an excellent state of conservation.

The dendrochronological samples of *Pinus sylvestris* have been drawn principally from the highest areas and the southern slopes, availing of what remains of the original forest mass that still preserves some aged individual specimens. In the course of the various studies we have carried out in the region over the last decades, we have established the existence of some specimens that are over 500 years old, the maximum known for this species so far in the Iberian Peninsula (Génova, 2000).

Moreover, some small pine forests or relictic stands of *Pinus nigra* have established themselves (occasionally mixed with *Pinus sylvestris* or *Pinus pinaster*) in the western area of Sierra de Guadarrama, growing on the hillsides above the Jarosa reservoir (Madrid), between 1200 and 1600 m (Génova et al., 1988; Regato et al., 1992). These populations form part of the most westerly natural distribution of this taxon in the world. Even though these trees display mainly narrow diameters and have reduced and flat treetops, they are the oldest known in the Sistema Central, some of them being more than 500 years old (Génova and Fernández-Cancio, 1998/1999; Génova, 2000).

The tree ring chronologies analysed here are elaborated on the basis of data from 15 sites in the Sierra de Guadarrama. Thirteen (13) sites correspond to populations of *Pinus sylvestris* and 2 to populations of *P. nigra* subsp. *salzmannii* (see Fig. 1). The data are derive both from sites studied by various authors and published in the "International Tree-Ring Data Bank" (ITRDB) – 8 sites, see Table 1 – and from other sites studied in Génova et al. (1993) and Génova (1994), also published in the ITRDB (Pedriza and Riscopol), together with others studied in Génova and Fernández-Cancio (1998/1999) (Jarosa, subsequently revised for this paper) or in Génova (2000) (Peñota, Cotos, Sietepicos) and, most recently (Valsaín), studied in Benso (2007) Génova et al. (2009).

The 13 sites of *Pinus sylvestris* are distributed in a range that is broad in both altitudinal (1385 m–2050 m) and spatial (8 sites with N or N-NE slopes and 5 with S slopes) parameters. As such, they are representative of the large surface area occupied by this pine in the region. By contrast, the altitudinal and spatial range of the sites of *Pinus nigra* analysed is much more limited (both are located on E slopes and are very close to each other, between 1400 m and 1600 m altitude), although as such they are also representative of the sparse distribution of this taxon in the Sierra de Guadarrama.

The structure and density of pine in the sampled site ranges from forest pine that is dense and adult and has been managed for over a hundred years (Valsaín), or more recently (Navafría), forest pine situated in protected areas with majestic specimens (Sietepicos, Cotos), through to stands with adult specimens and natural regeneration, and/or deriving from reforestation in formations subject to frequent fires (Pedriza, Riscopol).

In each locality a very variable number of specimens were analysed. Generally speaking, the number of samples has increased as the techniques of statistical analysis have improved. Sample numbers have risen from a minimum of 14 synchronised growth series per site (Pedriza) through to a maximum of 81 (Valsaín). In total, we have to date 445 individual growth sequences from 227 trees (201 of *Pinus sylvestris* and 26 of *Pinus nigra*) from the region. Local chronologies are very different so far as time span is concerned, ranging from a maximum of 530 years (1462–1992) in Jarosa, to a minimum of 187 years (1818–2005) in Valsaín, even though they present similar mean sensitivity and intercorrelation values (see Table 1). In Fig. 2 the 15 local chronologies are presented, together with the number of individual sequences replicating each year, extending in total from 1462 to 2005.

2.2 Significance and reliability of the chronologies; compilation of the regional chronology

Given that the available local chronologies present considerable variability with regard to the number of individual sequences and also the time span on which they are based, the representativity, significance and reliability of each chronology has been analysed using statistical techniques commonly employed in dendrochronological studies.

- Analysis of the Principal Components: A principal component analysis (PCA) based on the correlation matrix was calculated for the common period 1818–1977 to evaluate the shared variance of the chronology network. The broken stick test was performed to determine the significance of the components (Holmes, 1992). The variance explained by the first principal component (PC1) was used as indicator of the similarity among the chronologies.

- EPS (Expressed Population Signal): A value of EPS close to 0.85 constitutes an indicator of agreement of the sample chronology variance with that of the theoretical population chronology. Consequently, the value of this parameter means one reasonable choice suggested by Wigley et al. (1984) to represent an acceptable level of chronology confidence.

- IT (Intercorrelation): Relative intercorrelation compared with the other chronologies for the region in the different sub-periods studied by the COFECHA program

(Holmes, 1999). Finally, the periods that are well monitored and sufficiently reliable in each local chronology have been used to produce a single average regional chronology.

2.3 Extreme growth values and pointer years

The study of extreme growth values in event years and their significance can be approached from different points of view and using different methodologies (Schweingruber et al., 1990; Meyer, 1999; Neuwirth et al., 2007; Elferts, 2007). In this paper, the criteria indicated in Génova (2000) have in general been followed, with the study being amplified to the positive extremes. Thus, the extreme years have been determined through the application of a double criterion:

- that the values or indices of growth suppose a diminution or increase of more than 20 % with respect to the average of that year and the year that comes immediately before it;
- that in the indices of growth, a diminution or increase of one or more standard deviations is determined with respect to the chronological average.

Both criteria have been applied in a sequential manner. First of all, the individual growth series of each site have been analysed, and the extreme local years have been determined, considering that they are present in no less than 75 % of the series at least. Next, all of the local chronologies have been analysed following these same criteria; and finally, the regional chronology. In this way, both the years which show evidence of a brusque variation in growth with respect to what preceded them, and also the years of anomalous growth following more gradual variations have been identified. This method allows a very detailed analysis of the local and regional significance of extreme growth values, even though it is more restrictive if compared with the methods used in other studies (for example, Rolland et al., 2000; Neuwirth et al., 2007; Andreu et al., 2007). In this respect, it should be pointed out that the expression pointer year is used in this paper in accordance with the definition of Schweingruber (1990): "Concentration of cross-dated event years within a group of trees".

2.4 Meteorological data and climate-tree growth relationship

With the objective of explaining the climatic significance of pointer years, an analysis of the meteorological data for the area of study has been undertaken. In the Sierra de Guadarrama, only one station (Navacerrada) has been identified as having an extensive and continuous meteorological register. Furthermore, this station is representative of the climate of the central Iberian high mountains. The observatory is located in the vicinity of the Puerto de Navacerrada (province of Segovia), at 1890 m a.s.l., at 40°46′50″ latitude N and 4°00′37″ longitude W (Fig. 1). The meteorological record presents monthly precipitation and temperature data going back to 1943, indicating the typical characteristics of the climate of the high mountains of the Mediterranean, with a mean annual temperature in the order of 6.4 °C. Frosts can be counted on from the months of January through to April, in November and December, and probably in the other months also, with the exception of August. Precipitation is high throughout all months of the year (although November stands out as having the highest rainfall), except in July and August, which constitute a period that presents certain aridity. Mean annual precipitation is around 1296 mm, while summer rainfall (combining July and August) is around 50 mm, with the latter being even more irregular in its interannual variabilility. The annual, monthly and seasonal oscillations of temperature and precipitation of this record have been analysed in detail, and the principal climatic anomalies occurring in the course of the studied period have been determined.

The relationships between growth and climate correlation and response function analyses were performed using the program Dendroclim2002 (Biondi and Waikul, 2004), both in the local chronologies and in the regional chronology. Climate-growth relationships were analyzed from the previous July up to October of the growth year with the aim of identifying the meteorological variables that correlated most with tree growth. Subsequently, we analyzed the relationship between the pointer years of the chronologies and climate anomalies.

3 Results

3.1 Analysis of the reliability of the chronologies and compilation of the regional chronology

Figure 4a shows the spatial disposition of the local chronologies with respect to the first two principal components that have been analysed. No value that was anomalous or that deviated much from the general range was obtained, so all the chronologies have been accepted in carrying out this study.

The PC1 and PC2 of the chronology network were significant, representing 44.09 % and 13.29 % of the total variance respectively, and the scatter plot of the PC loading coefficients displayed groups of chronologies with similar growth patterns (Fig. 4a). Although the chronologies showed different loadings with the PC1, all of them had positive correlations with it, showing that they shared a common variance. *P. sylvestris* chronologies were scattered, covering nearly the whole range of the first axis values, while the chronologies of *P. nigra* have values similar to the lower range of those reported in *P. sylvestris*. The differences determined in the PC1 could be related to micro-environmental diversity and, more specifically, to differences in altitude (Fig. 4b). On the other hand, one chronologies group was mainly positively correlated with the PC2, while the other was negatively correlated with it (Fig. 4a). The first corresponds with southern or eastern chronologies, the second with northern chronologies; in no case the PC1 and PC2 have shown significant differences between species.

Furthermore, the discriminating values of the statistics used to analyse the reliability and significance of the time span covered by the chronologies is shown in Table 2. In some of the oldest chronologies, it has not been possible to obtain an EPS value equal or superior to 0.85 due to the low number of individual sequences contained by said chronologies. Even so, it has seemed of interest to us to utilise them in subsequent analyses.

Comparing the time span in which EPS is equal or superior to 0.85 and the period from which there is a correlation superior to 0.32 according to the cross-dating, it is possible to observe many cases where there are notable differences (see Table 2). It has been decided that, both for the compilation of the regional chronology and for the study of anomalies in the width of the growth rings, the period determined by the cross-dating quality control determined by the statistical program COFECHA is reliable. Consequently, once the significance, representativity and reliability of the different sub-periods of the local chronologies have been established, a representative regional chronology of the variability of the tree rings of *Pinus sylvestris* and *Pinus nigra* in the Sierra de Guadarrama has been compiled.

3.2 Relationships between the chronologies and the meteorological record

The general relationship between the variability of the growth indices and the climate has been studied by analysing the values of the significant coefficients of the response function obtained for each local chronology and also for the regional chronology, both in relation to the analysed variables of the growth year (n) and of the previous year ($n-1$) (Fig. 5). The variables relating to precipitation most of all in the month of August and, to a lesser degree, precipitation during the month of July (in both cases corresponding with the growth year) are those where the chronologies present the greatest sensitivity; furthermore, in the regional chronology August precipitation is alone in presenting significant value. On the other hand, it is almost only the chronologies of *Pinus nigra* which present a certain relationship with the climatic variables of the previous year, as has already been pointed out in Génova (1994), Génova and Fernández (1998–1999) and Génova et al. (1997).

3.3 Pointer years, variability over time, and significance

Using the criteria described in Material and Methods, extreme growth values and pointer years in individual chronologies, local chronologies and in the regional chronology have been identified. In Table 3, only extreme growth values coinciding with respect to the first criterion in 75 % or more of the local chronologies covered by these dates, and those which fulfil the second criterion in the regional chronology are presented. These selected pointer years have been assigned a relative value of their significance (between ±1 and ±3), which likewise are shown in Table 3 and in Fig. 6. In total, 64 pointer years have been identified: 30 negative (representing minimum growths) and 34 positive (representing maximum growths). This represents some 15 % of the total number of years analysed (405 years, 1600–2005). In this same table there have also been added some references to European compilation studies for those cases where there are coincidences with the pointer years defined for the Sierra de Guadarrama. Furthermore, the climatic characteristics for these pointer years with respect to summer precipitation have been pointed out. As has been seen in the previous section, this is the variable most related to growth variations in the Sierra de Guadarrama. In the period 1943–2005, the data derive from the Navacerrada record, while the information provided for the previous years proceeds from bibliographical sources based on a variety of evidential material.

A frequent occurrence is pointer years that come together in pairs, or in longer periods constituting pointer intervals (Schweingruber et al., 1990). Among the biennial intervals, one could point out those which coincide in sign and value (1649–1650, 1707–1708, 1715–1716, 1762–1763, 1771–1772, 1793–1794, 1813–1814, 1814–1815, 1903–1904), or in sign but with different values (1600–1601, 1601–1602, 1688–1689, 1737–1738, 1771–1772, 1941–1942, 1958–1959, 1962–1963). Other noteworthy periods are those where various extremes are concentrated, such as the unfavourable three years from 1600–1602 and six years from 1960–1965 (the most striking in the whole register), and the favourable five years from 1734–1738 (the most striking in the whole register) or 1811–1815.

The importance of the pointer years has been studied for each century (see Fig. 6 and Table 4). The 17th and 20th centuries are those which present the highest percentage of extreme years (16 % and 23 % respectively), with the last century being particularly noteworthy in this regard. With respect to variability of tree growth, the 19th century is the most homogeneous and stable, and presents a smaller number of anomalies (11 %). The distribution of anomalies, in turn, is different in each century: the 18th and 19th centuries present a similar distribution, with a third of negative extremes and two-thirds of positive extremes. For its part, the 17th century presents the reverse of this distribution; with much more frequent negative extremes (75 %), making it consequently the most unfavourable century for growth. In the 20th century, on the other hand, the distribution between negative and positive is fairly balanced.

Both the first half of the 17th and the second half of the 20th centuries present a great number of extreme years (19 in total), and of maximum negatives (1601, 1963 and 1996), while the years most favourable for growth are to be found in the first half of the 18th century, with few negative pointer years and only two maximum positives (1734 and 1737). Finally, it is worth pointing out that the year 1601 is the most anomalous of the whole register, with an average index of growth that is lower than the average by almost three standard deviations.

4 Discussion

4.1 Pointer years and regional chronology of the Sierra de Guadarrama

The analysis of the local chronologies compiled for the Sierra de Guadarrama has made it possible to identify a period (1600–2005) which is sufficiently reliable for the determination of extremes in the tree-rings. Moreover, no significant differences have been observed between the chronologies of *Pinus sylvestris* and *P. nigra*, and all of them have been used in the compilation of a regional chronology. Both the list of pointer years augmented with respect to the data processed in Génova (1994, 2000), as also the compilation of a single regional chronology, can be used to synchronise and date new series of growth. A very recent demonstration of this utility has been the dendrochronological dating of historic wood originating from the Old Mint in Segovia (Génova et al., 2011). Furthermore, this record of pointer years in Central Spain provides information regarding their significance and distribution over the last 405 years, which can be contrasted with other extensive dendrochronological records of *Pinus* from throughout Spain (Andreu et al., 2007; Bogino et al., 2009; Génova, 1998; Génova and Fernández, 1997–1998; Génova et al., 2009) in order to characterise anomalies of growth indicating macro-climatic events in the Iberian peninsula.

The year 1601 is registered in the tree rings of Central Spain as the most unfavourable for growth of the last 405 years. As Génova (2000) already noted "... 1601 was the only year in which the indices of regional chronologies were lower than two standard deviations from the mean". This fact coincides with many other anomalies dated to this year in the tree rings of the Northern Hemisphere. For example, as Hantemirov et al. (2004) have emphasised, "Anomalous tree rings were formed in many regions in 1601. A large proportion of the samples from the Polar Urals and Yamal Peninsula have frost or light rings in 1601.". Furthermore, the importance of 1601 as a pointer year for synchronising historic wood in Central Spain has very recently been pointed out by Génova et al. (2011). It was not for a long time, not until the 20th century, that other pointer years of comparable significance were identified. 1963 also represents a very significant reduction in growth, having already been cited by Richter (1988) as the only pointer year common to *Pinus sylvestris* in this same geographical area. It is situated in the middle of the initial six years of the 1960s which, in general, constituted in the centre of Spain a period that was very unfavourable for tree growth (Génova, 2000). 1996 is a negative pointer year of less significance, because it is represented for the moment in the Sierra de Guadarrama by only one site, even though 100 % of the trees studied there present a notable reduction in growth for that year. Hantemirov (2004) also has found anomalies in that year in various species of northwest Siberia.

4.2 Climatic significance of pointer years in the second half of the 20th century

The anomalous meteorological years of the Navacerrada register have already been analysed in detail in Génova (2000), with the aim of establishing correlations with the extreme reductions of growth. Amplifying the temporal range of the study to 2005, and taking into consideration also the positive extremes, it has been proved that in quite a number of cases the anomalous meteorological years could explain the pointer years, even though a complete biunivocal correspondence does not exist. Given that summer precipitation has been the most incident factor in the general variability of growth of *Pinus* in the Sierra de Guadarrama in the second half of the 20th century (see Sect. 3.2), it is also an explanatory factor in almost 50 % of the extreme growths.

The pointer years 1962, 1963 and 1965 could well correspond with the period of dry summers of the first half of the 1960s (even though these years were dry in general throughout Spain, according to Vicente-Serrano, 2006). The negative 1986 ring was formed after the dry year of 1985; while 1959, 1973 and 1976 correspond with damp years (see Fig. 7). These results are coherent with those obtained by Lebourgeois (2000) for *Pinus nigra* in western France, with many points of agreement being identified between extreme low-growth years and summer drought (low and high values of precipitation and temperature during the growing season).

Nevertheless, other positive pointer years identified in the chronologies of the Sierra de Guadarrama – 1958, 1964, 1980 and 1994 – do not appear to have any clear climatic explanation, even when taking into account the anomalies of temperature of the month of April. This last-mentioned meteorological variable also seems to have a considerable effect on the width of the rings in Central Spain, according to Génova (2000), and could explain the positive extremes of 1943 and 1945, and also the negative extreme of 1986. Although this last pointer year has not been registered in the most recent European compilations, Lebourgeois (2000) does draw attention to it in the chronologies of *Pinus nigra* in western France, indicating that it cannot be associated with a rainfall deficit but seems to be linked to extreme frost in February.

The year 1996 was a year of extreme reduction in growth, and even though we only have data corresponding with one site (Valsaín), 100 % of the trees present a narrow ring for that year. It could be that the storm of January 1996, which caused damage extending over 6600 ha of this site (more than 80 % of the forest's total surface), and leading to the cutting of an enormous amount of wood – the most in the last 50 years, according to Donés and Garrido (2001) – affected the normal development of the cambium in this year. Furthermore, even though neither that year nor the previous ones were notably dry in the summer, the six years from 1990–1995 do, nevertheless, constitute the driest period of the whole register so far as annual precipitation is concerned. Indeed, the decade of the 1990s was noteworthy for having seen one of the more extreme droughts that affected a major part of the Peninsula (Vicente-Serrano, 2006), and quite possibly the lack of phreatic water affected the formation of the ring. Once more data are available, it will be possible to compare and determine whether the event was local or more general.

4.3 Temporal distribution of pointer years and their significance in Central Spain

Our data show that there has been variability over the centuries in the distribution of the frequencies of pointer years and intervals. This variability was sufficiently notable to enable us to affirm that both in the 17th and 20th centuries the macroclimatic anomalies that affected growth were more frequent and more extreme than in the other two centuries analysed. This dendroclimatic characterisation of the last four centuries of the last millennium, based as it is on the distribution and significance of the characteristic years, coincides in general terms with the data that refer to the historic information relating to the climate of the Iberian Peninsula compiled by Fernández and Manrique (1997). These authors analyse the number of data available in each decade relating to droughts, heavy rainfall and flooding, severe cold, frosts and high temperatures, from the years 1100 to 1900. Their conclusion, even having taken into account the subjectivity relating to this type of information, is that the period from 1500 to 1700 presents a greater amount of news relating to climatic extremes than the two subsequent centuries. This enables us to identify with some precision the length and the characteristics in Spain of the Little Ice Age (LIA) which drew to an end at the beginning of the 18th century. Numerous studies of historical climatology carried out subsequently in Spain are laying the methodological groundwork for an objective record of the historical news relating to the climate (Barriendos, 1997; Domínguez-Castro et al., 2010; Rodrigo and Barriendos, 2008). So far as Central Spain is concerned, these events are expressed in the work of Bullón (2008), and Domínguez-Castro et al. (2008).

Negative pointer years are much more abundant over the course of the 17th century, particularly in the first half of the century, which presents the highest concentration of extreme negative years for tree growth (9 years). By contrast, in the 18th century there are abundant positive extremes, indicating a period that is generally favourable for the growth of trees. This only partially matches the reconstruction of drought episodes for Central Spain from rogation ceremonies (Domínguez-Castro et al., 2008). These indicate that two drought maxima appear during the 1600–1675 and 1711–1775 periods, since in the latter period the tree rings do not indicate significant negative anomalies. By contrast, there is coincidence with a middle stage (1676–1710) when droughts were less frequent and their length shortened (Domínguez-Castro et al., 2008), and with the hypothesis that the Maunder Minimum (1645–1715) marks the transition from the dry conditions of the sixteenth and early seventeenth century to the longest wet period in the Iberian Peninsula, between 1670–1765 (Domínguez-Castro et al., 2010). For its part, the 19th century presents very few pointer years, and seems to have been in common the least unfavourable for growth, coinciding with the fact that the few droughts show the minimum values of the series and are all below the average (Domínguez-Castro et al., 2008). It could be that the existence of more frequent negative NAO atmospheric conditions during the 18th and 19th centuries (Luterbacher et al., 2002; Pauling et al., 2006) explains the preponderance of damp conditions over that period.

The second half of the 20th century and the first half of the 17th century together constitute the two most notable periods for the frequency of negative pointer years in Central Spain. This was particularly the case during the decade of the 1960s, which saw an almost continuous period of six years where the indices of growth were below average. Even though specific years are not referred to, this same period is clearly reflected in Fig. 4 of the extensive study of Andreu et al. (2007), with chronologies from the north and east of the Iberian Peninsula. Nevertheless, this period does not appear to have had the same significance in other European areas, since only 1962 and 1965 appear indicated as pointer years by Neuwirth et al. (2007), with 1965 representing positive and negative anomalies depending on the region. Andreu et al. (2007) show that the higher occurrence in Spain of extreme years and the sensitivity increase in the second half of the 20th century were in agreement with an increment in precipitation variability during the growing period, as indicated by Font Tullot (1988), Romero et al. (1998), De Luis et al. (2000), Giorgi et al. (2004). Nevertheless, Vicente-Serrano (2006) points out that the most intense droughts were recorded in the 1940s, 1950s, 1980s and 1990s. Thus, there does not appear to be any clear explanation on the basis of these data, making it necessary to have recourse to other sources.

4.4 Events of special relevance

The period 1600–1602 is one of the most unfavourable for tree growth in the centre of Spain, and 1601 is the minimum index in the regional chronology. As has already been pointed out, this coincides with many other anomalies dated to that year in the tree rings of the Northern Hemisphere. Hantemirov et al. (2004) relate these anomalies with some global event that left its trace in the tree rings of woody plants. According to Briffa et al. (1998), this was the most severe short-term Northern Hemisphere cooling event of the past 600 years. Continuing with an already long tradition that relates the most notable volcanic eruptions to growth reduction or other anomalies in tree-rings (e.g. LaMarche and Hirschboeck, 1984; Scuderi, 1990; Jones et al., 1995, among others), it is possible to infer that these phenomena are the effect of the eruption of

Huaynaputina, which occurred in Peru at the beginning of 1600 AD (Briffa et al., 1998). According to these anomalies and to other proxies, this was the biggest eruption in the world in the last 600 years (Briffa et al., 1998; de Silva and Zielinski, 1998; Hantemirov et al., 2004). Nevertheless, this is the first time that the effects of this eruption in the tree-ring records of central and southern Europe have been demonstrated. It needs to be emphasised, moreover, that the effects of this volcanic eruption were registered in the Sierra de Guadarrama as pointer years during a whole three years, from the starting year, 1600, until 1602. On the other hand, there has been no evidence of the effects of other more recent eruptions in the chronologies that have been analysed.

While the authors who have analysed this particular macroclimatic event and its consequences for tree growth have attributed its effects to the severe cooling event (Hantemirov et al., 2004; Briffa et al., 1998), some climatic reconstructions of the central Iberian Peninsula have also indicated that the start of the 17th century was very dry (Domínguez-Castro et al., 2008). It could be that this volcanic eruption caused both climatic anomalies in this period in Central Spain, or it could also be that its effects on tree growth are more related with the reduction of solar energy due to the accumulation of ash in the atmosphere, and the consequent diminution of photosynthesis. This hypothesis can also perhaps help to explain the pointer interval at the start of the 1960s, although since we know of no large-scale eruptions in this period, the accumulation of ash and other particles in the atmosphere could be of anthropic origin (pollution, atomic weapons testing, etc.).

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. General Characteristics of the Chronologies developed in Sierra de Guadarrama.

Site name	Site code	Species	Latitude/ Longitude	Elevation (m a.s.l.)	Aspect	N_t^3	N_s^4	M_s^5	IT[6]	Time Span	Author/s
Puerto de Navacerrada	NAV	Pisy[1]	40°48′/4°02′	2050	N	13	24	0.22	0.488	1663–1977	Bräker and Schweingruber, (1984) (ITRDB)
Guadarrama -Camorca	CAM	Pisy[1]	40°49′/4°03′	1550	N	13	27	0.31	0.618	1726–1983	Richter (1988) (ITRDB)
Guadarrama -Iniesto	INI	Pisy[1]	40°48′/3°59′	1800	N	20	39	0.26	0.545	1749–1983	Richter (1988) (ITRDB)
Guadarrama -Loma de Noruego	NOR	Pisy[1]	40°47′/3°58′	1950	N	14	26	0.23	0.534	1661–1985	Richter (1988) (ITRDB)
Guadarrama -Rascafria	RAS	Pisy[1]	40°48′/3°57′	1850	N	10	23	0.24	0.566	1599–1984	Richter (1988) (ITRDB)
Navafria I	NF1	Pisy[1]	40°59′/3°48′	1900	S	18	30	0.22	0.532	1685–1992	Yuste (1994) (ITRDB)
Navafria II	NF2	Pisy[1]	40°58′/3°48′	1630	S	13	24	0.24	0.626	1787–1992	Yuste (1994) (ITRDB)
Navafria III	NF3	Pisy[1]	40°58′/3°47′	1525	S	10	28	0.24	0.692	1791–1992	Yuste (1994) (ITRDB)
Pedriza	PED	Pisy[1]	40°45′/3°53′	1650	S	7	14	0.27	0.556	1715–1988	Génova (1994) (ITRDB)
Penota	PEN	Pisy[1]	40°44′/4°06′	1650	S	9	18	0.27	0.554	1763–1991	Génova (2000)
Sietepicos	SIE	Pisy[1]	40°47′/4°01′	1950	N	17	31	0.21	0.558	1527–1995	Génova (2000)
Cotos	COT	Pisy[1]	40°48′/3°58′	1900	N	14	29	0.22	0.515	1513–1994	Génova (2000)
Valsain	VAL	Pisy[1]	40°50′/4°02′	1400	N-NE	43	81	0.29	0.549	1818–2005	Benso (2007)
Riscopol	RIS	Pini[2]	40°40′/4°10′	1600	E	11	24	0.26	0.676	1523–1988	Génova (1994) (ITRDB)
Jarosa	JAR	Pini[2]	40°40′/4°09′	1400	E	15	27	0.27	0.590	1462–1992	Génova and Fernández-Cancio, 1998/1999, revised for this paper

[1] Pisy: *Pinus sylvestris*,

[2] Pini: *Pinus nigra*,

[3] N_t: number of trees,

[4] N_s: number of sequences,

[5] M_s: mean sensitivity of raw sequences in each site,

[6] IT: intercorrelation of raw sequences in each site

Table 2. Characteristics of reliable time span of local chronologies of Sierra de Guadarrama.

ID	EPS[1]	Time span	N_s[2]	N_t[3]	M[4]	SD[5]	Segment correlation														
							1600 1649	1625 1674	1650 1699	1675 1724	1700 1749	1725 1774	1750 1799	1775 1824	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999
NAV	0.853	1849–1954	18	10	.988	.167							.59	.43	.32	.51	.55	.56	.71	.70	.70
CAM	0.843	1885–1983	17	10	.980	.232						.41	.50	.58	.47	.47	.62	.65	.50	.43	.53
INI	0.857	1806–1971	22	12	.993	.185						.52	.55	.79	.42	.43	.74	.79	.80	.75	.74
NOR	0.826	1829–1985	11	7	.988	.192			.55	.63	.72	.60	.47	.67	.68	.68	.70	.74	.79	.76	.77
RAS	0.786	1741–1912	15	7	.992	.151					.55	.62	.61	.66	.49	.51	.64	.69	.73	.75	.77
NF1	0.846	1825–1992	17	12	.987	.155							.61	.62	.58	.64	.76	.76	.82	.83	.73
NF2	0.828	1850–1992	16	9	.988	.192								.53	.52	.63	.66	.68	.76	.71	.81
NF3	0.913	1876–1992	23	10	.992	.202								.39	.37	.39	.51	.63	.67	.63	.72
PED	0.805	1900–1988	14	7	.992	.203							.52	.60	.69	.62	.47	.60	.64	.50	.64
PEN	0.770	1842–1983	18	9	.989	.185							.37	.46	.53	.57	.58	.65	.75	.66	.61
SIE	0.872	1600–1988	17	11	.989	.161	.34	.35	.19	.27	.44	.60	.70	.76	.65	.54	.51	.57	.68	.65	.37
COT	0.836	1775–1990	18	11	.987	.159	.52	.38	.44	.49	.46	.61	.70	.75	.69	.68	.56	.63	.69	.58	.68
VAL	0.908	1867–2005	26	16	.984	.194											.36	.53	.55	.51	.55
RIS	0.843	1775–1940	13	6	.999	.192	.75	.55	.31	.39	.08	.08	.56	.64	.53	.54	.63	.61	.61	.65	.64
JAR	0.801	1600–1990	15	8	.985	.193	.53	.41	.48	.43	.19	.20	.41	.62	.59	.58	.66	.64	.61	.61	.68

[1] EPS: Expressed Population Signal,

[2] N_s: number of sequences,

[3] N_t: tree number,

[4] M: mean value,

[5] SD: standard deviation.

Table 3. Pointer years in Sierra de Guadarrama. % LC: percentage in which there is a coincidence higher than 75 % among local chronologies. RGI ± SD: years whose regional growth indices exceeded one or more SD (standard deviation), 1 SD< * <2 SD, ** >2 SD. Value: relative value of the pointer year based on its significance, 1: it is only presented in one of the two previous columns, 2: it is presented in the two previous columns, 3: the indices values exceed 2 SD wich are shown shaded. Climate SG: climate of Sierra de Guadarrama, between 1943 and 1996 according to data from Navacerrada station, FT1: data extracted from Fontana Tarrats (1977), FT2: data extracted from Font Tullot (1988).

Year	Sign	% LC	RGI ± SD	Value	Climate	Other European References
1600	–		*	1		
1601	–	100 %	**	3		Hantemirov et al. (2004)
1602	–	100 %	*	2		
1620	+		*	1		
1622	+		*	1	Droughts (FT1)	
1623	–	75 %		1	Droughts (FT1)	
1624	–	75 %	*	2		
1633	–	75 %	*	2	High Rainfall (FT1)	
1645	+	75 %	*	2	Droughts (FT1)	
1646	–	75 %		1	Droughts (FT1)	
1649	–		*	1	Droughts (FT1)	
1650	–		*	1	Droughts (FT1)	
1659	–	75 %	*	2	Droughts (FT1)	
1660	+	75 %		1		
1688	–	80 %	*	2		
1689	–		*	1		
1707	–		*	1	High Rainfall (FT2)	
1708	–		*	1		
1715	+		*	1		
1716	+		*	1		
1734	+		**	3		
1737	+		**	3		
1738	+		*	1	Droughts (FT2)	

Table 3. Continued.

Year	Sign	% LC	RGI ± SD	Value	Climate	Other European References
1762	+		*	1		
1763	+		*	1		
1771	–		*	1		
1772	–		*	1		
1788	+		*	1		
1793	+		*	1		
1794	+		*	1		
1803	–		*	1	Droughts (FT2)	
1806	–		*	1		
1807	+	86 %		1		
1811	+		*	1		Hantemirov et al. (2004)
1813	+		*	1		
1814	+		*	1		
1815	+		*	1		
1869	+		*	1		
1879	–		*	1	Droughts (FT2)	Hantemirov et al. (2004)
1893	+		*	1		
1894	–	87 %		1		
1903	+		*	1		
1904	+		*	1		
1914	+		*	1		
1921	–		*	1	Droughts (FT2)	Neuwirth et al. (2007) (±)
1923	+	80 %	*	2		
1924	–	100 %		1		
1941	–	80 %	*	2		Hantemirov et al. (2004)
1942	–		*	1		Neuwirth et al. (2007)
1943	+	80 %		1	Normal year	
1945	+		*	1	Driest year of the record	
1958	+		*	1	Normal year	Hantemirov et al. (2004)
1959	+		*	1	Damp year	
1960	–	80 %		1	Start of a dry decade	
1962	–	80 %	*	2	Dry year	Neuwirth et al. (2007) (±)

Table 3. Continued.

Year	Sign	% LC	RGI ± SD	Value	Climate	Other European References
1963	–		**	3	Dry year	
1964	+	100 %		1	Damp year	
1965	–		*	1	Dry year	Neuwirth et al. (2007) (±)
1973	+	87 %		1	Damp year	
1976	+		*	1	Wettest year of the record	
1980	+		*	1	Normal year	Hantemirov et al. (2004)
1986	–	100 %	*	2	End of a very dry two years	
1994	+		*	1		
1996	–		**	3	Normal year	Hantemirov et al. (2004)

Table 4. Distribution of pointer years and intervals in the four centuries analysed in Sierra de Guadarrama. The shaded years correspond to negative pointer values.

Century	Pointer years and pointer intervals
XVII	1600–1602, 1623–1624, 1633, 1646, 1649–1650, 1659, 1688–1689
	1620, 1622, 1645, 1660
XVIII	1707–1708, 1771–1772
	1715–1716, 1734, 1737–1738, 1762–1763, 1788, 1793–1794
XIX	1803, 1806, 1879, 1894
	1807, 1811, 1813–1815, 1869, 1893
XX	1921, 1924, 1941–1942, 1960, 1962–1963, 1965, 1986, 1996
	1903–1904, 1914, 1923, 1943, 1945, 1958–1959, 1964, 1973, 1976, 1980, 1992, 1994

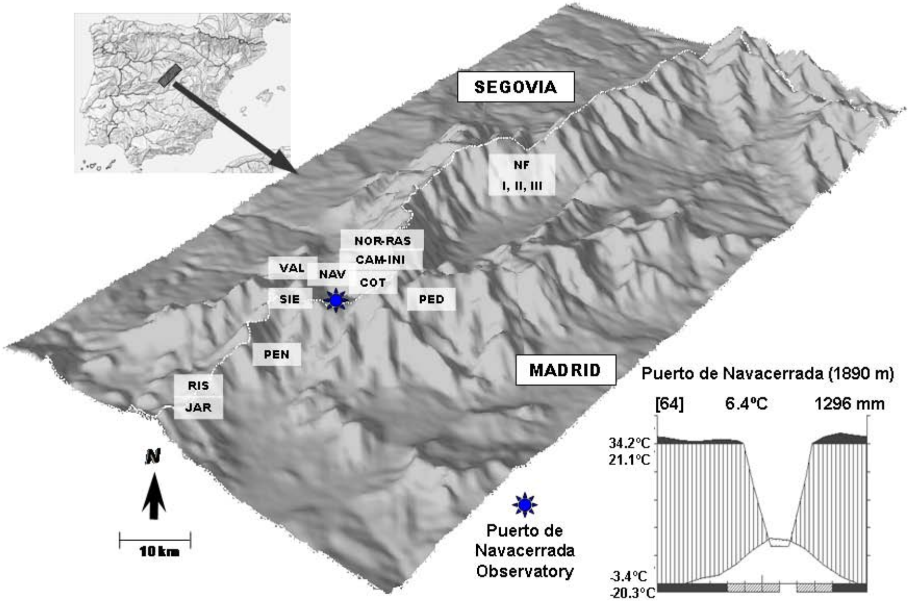

Fig. 1. Geographical position of the studied sites in the Sierra de Guadarrama (between the provinces of Segovia and Madrid, Spain), location of Puerto de Navacerrada meteorological observatory and climate diagram.

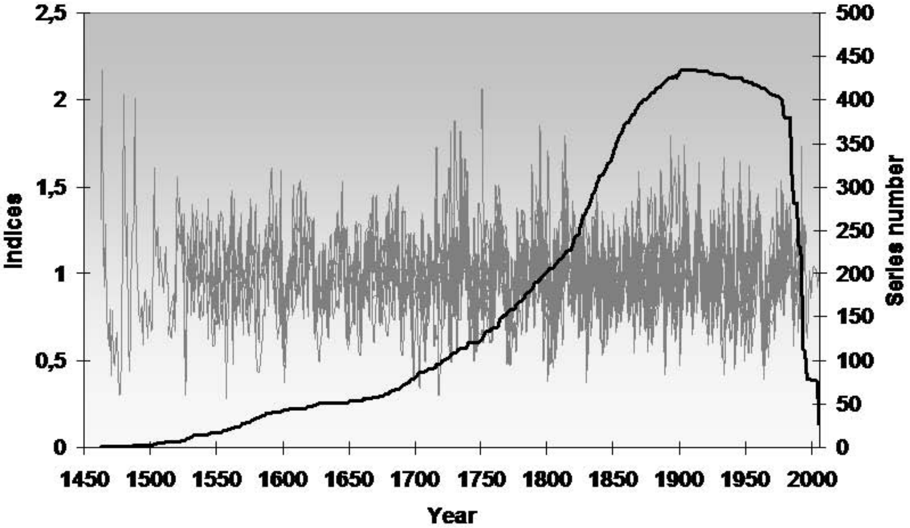

Fig. 2. Local chronologies developed in the Sierra de Guadarrama and the total number of tree-ring series in each year.

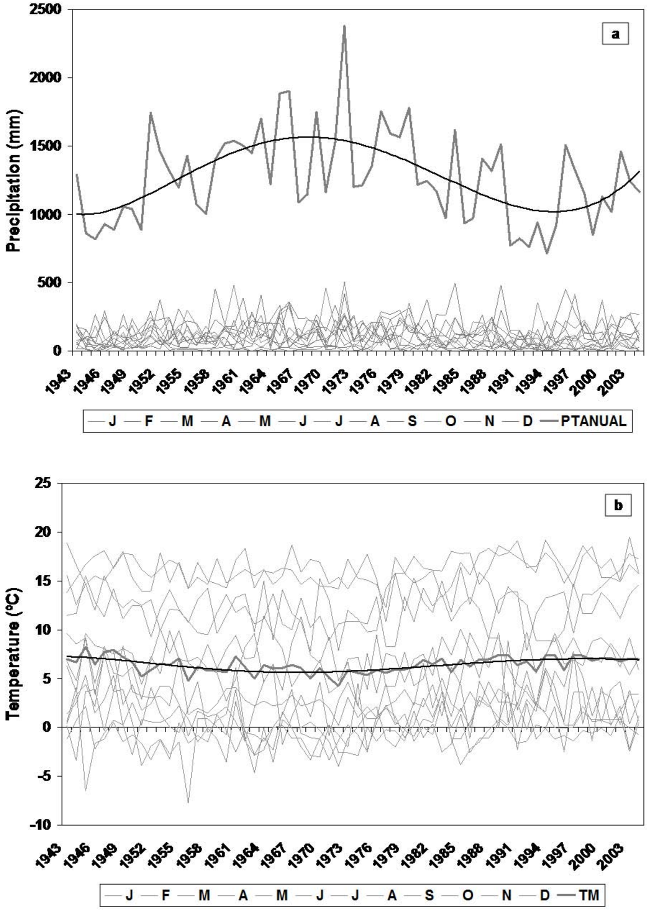

Fig. 3. Oscillations of monthly and annual precipitation **(a)** and of monthly and annual mean temperature **(b)**, recorded in Navacerrada station along the period under review; trends in annual precipitation and mean annual temperature are show according to a polynomial model of order 5.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
|◀ ▶|
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

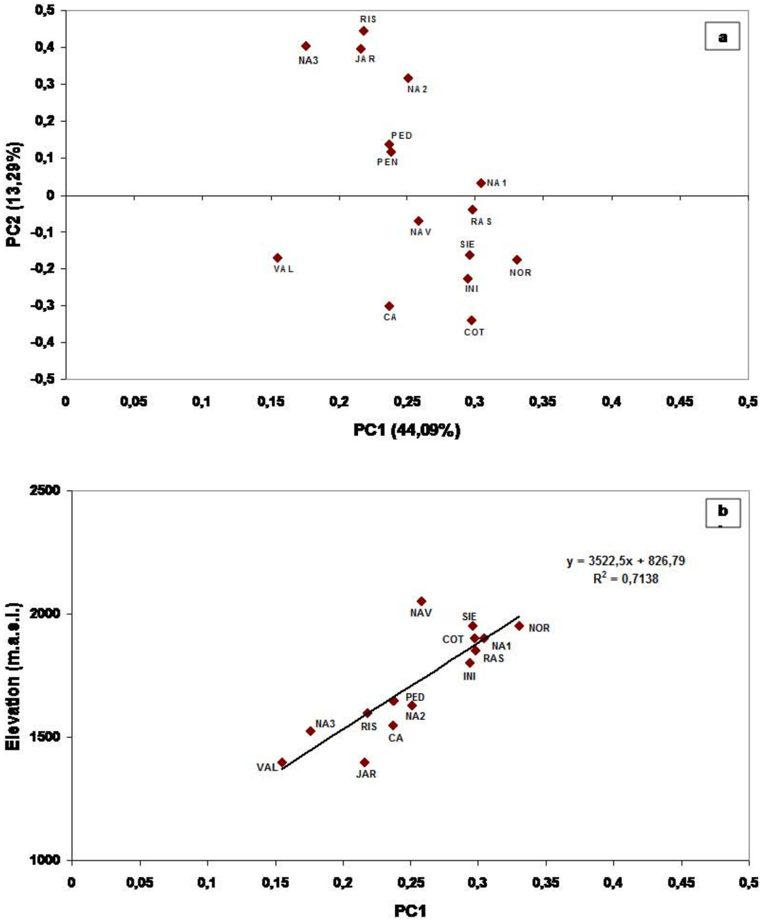

Fig. 4. Scatter plots of principal component analysis (PCA) loadings of the 15 chronologies for the period 1818–1977 **(a)** and correlation and linear regression between PC1 and altitude **(b)**.

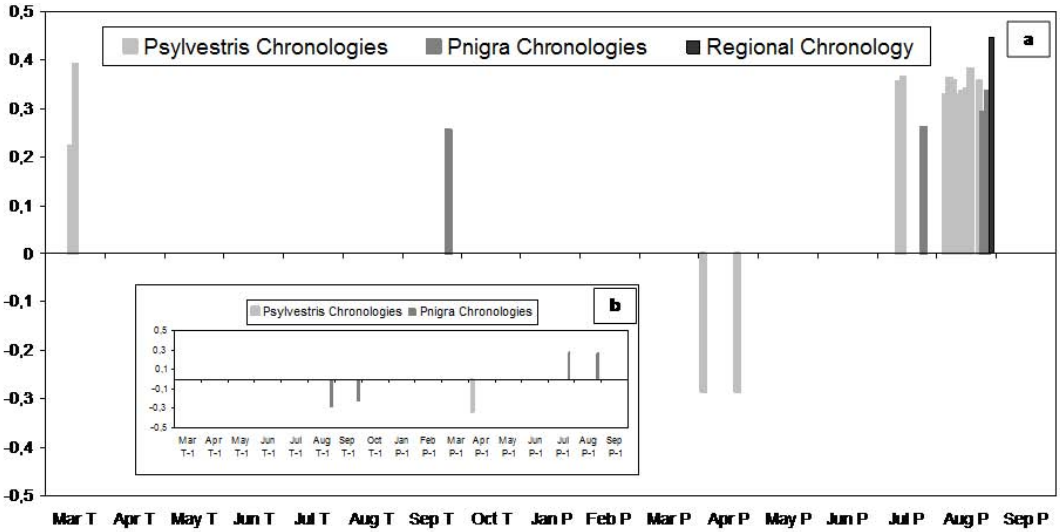

Fig. 5. Bootstrap response significant values for the year of growth **(a)** and Bootstrap response significant values for the previous year of growth **(b)**.

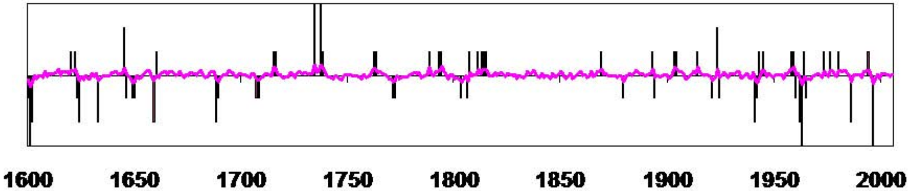

Fig. 6. Distances of regional chronology of Sierra de Guadarrama to the average (pink solid line) overlying pointer years and intervals (black columns) according to their relative value – see Table 3 – over the last four centuries.

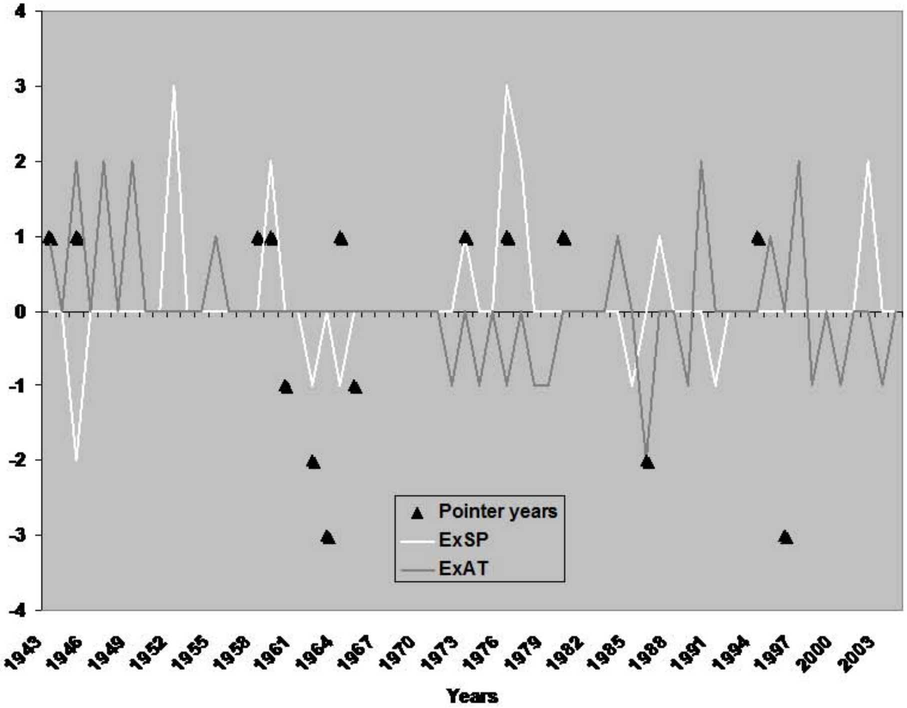

Fig. 7. Pointer years (triangles) and climate extreme years (solid line) in Sierra de Guadarrama. ExSP: extreme Summer Precipitation, ExAT: extreme April Temperatures.