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Ecological response of *Cedrus atlantica* to climate variability in the Massif of Guetiane (Algeria)

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Abstract

Aim of the study: The study analyzes the long-term response of Atlas cedar, *Cedrus atlantica* (Manneti), to climate variability.

Area of study: Atlas cedar forest of Guetiane (Batna, Algeria).

Material and methods: The dendrochronological approach was adopted. An Atlas cedar tree-ring chronology was established from twenty trees. The response of the species to climate variability was assessed through the pointer years (PYs), the common climate signal among the individual chronologies, expressed by the first component (PC1), the mean sensitivity (ms_x), and response function and correlations analysis involving the tree-ring index and climate data (monthly mean temperature and total precipitation).

Results: The highest growth variability was registered from the second half of the 20th century. The lower than the mean PYs, the PC1, and the ms_x increased markedly during the studied period. Dramatic increases in the PC1 and ms_x were detected at the end of the 1970s, reflecting a shift towards drier conditions enhancing an increasing trend towards more synchronous response of trees to climate conditions. The response function and correlations analysis showed that tree growth was mainly influenced by precipitation variability.

Research highlights: Our findings provide baseline knowledge concerning the ecological response of Atlas cedar to climate variability in in its southern distribution limit, where a high level of tree mortality has been observed during recent decades, coinciding with the driest period Algeria has ever experienced. This information is vital to support ongoing ecosystem management efforts in the region.

Key words: Atlas cedar; annual growth variability; dieback; dendrochronology.

Introduction

The climate has changed over the past century and it is expected to continue to change in the future (IPCC, 2007), resulting in warmer temperatures and changed precipitation regimes (Chmura *et al.*, 2011). Consequently, changes in the distribution of plants species are expected (Demarteau *et al.*, 2007). An understanding of plant responses to fluctuations in the environment is critical to predictions of plant and ecosystem responses to climate change (Chapin *et al.*, 1993) and constitute a valuable tool for forest management. The current climate change is significantly affecting Mediterranean forests (Resco de Dios *et al.*, 2007). Recent studies in northwestern Africa reported recurrent drought events over the last few decades (Touchan *et al.,* 2008a, 2010; Linares *et al.*, 2011; Kherchouche *et al.*, 2012, 2013), suggesting climate conditions more limiting to tree growth and drought-sensitive species geographical distribution, especially for those at the edge of their range (Fritts, 1976). Atlas cedar, *Cedrus atlantica* (Manneti), is a drought-sensitive tree that could be affected by recent climate variability. During recent decades, high rates of mortality have been reported in Algeria (Alileche, 2012; Megdoud, 2012; Kherchouche *et al.*, 2013) and Morocco (El Abidine, 2003; Linares *et al.*, 2011). In Algeria, Allen *et al.* (2010) reported that the recent *C. atlantica* mortality began as small patches on drier aspects in the arid near-Sahara mountains, eventually coalescing into large patches affecting all ages on all exposures. In contrast, only small patches of old trees on dry aspects have died in more mesic regions near the coast. Extreme cases

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were observed in the region of Batna (Bentouati, 2008; Kherchouche *et al.*, 2013). The National Park of Belezma recorded the highest level of tree mortality: in Djebel Tuggurt, wide areas showed forest decline and mortality and were invaded by *Fraxinus xanthoxyloïdes*, whereas in Djebel Boumerzoug *C. atlantica* almost disappeared and the space has been invaded by another drought-tolerant species, *Quercus ilex*. In Morocco, Mokrim (2009) and Linares *et al.* (2011) reported similar results. Linares *et al.* (2011) noticed that *C. atlantica* forests that have experienced severe drought in combination with grazing and logging may be in the process of shifting dominance toward more drought-tolerant species such as *Q. rotundifolia*. Benabid (1994) noticed that a steppization process is increasingly affecting *C. atlantica* forests in the Atlas Mountains, in Morocco, and in the massifs of El Hodna, Belezma and the Aurès, in Algeria. Cheddadi *et al.* (2009) reported that environmental changes in northern Africa since the last glacial period have had an impact on the geographical distribution of *C. atlantica* and on its modern genetic diversity, and it is possible that by the end of this century *C. atlantica* may be unable to survive in its present-day locations.

The current study deals with the ecological response of *C. atlantica* to climate variability from 1850 to 2009 in its southern distribution limits. To the best of our knowledge, this is the first long-term radial growth-climate interaction investigation in the Massif of Guetiane (western Batna, Algeria). The dendrochronological approach was adopted. Twenty trees were sampled in 2010, at the highest elevations, from east to west along the northern facing slope of the mountain, where a lower rate level of dieback was registered. The established chronologies were used to analyze the impact of climate variability on tree growth through trends in response with a common growth variability of the samples and their mean sensitivity evolution throughout time. The main objectives of this study were *(i)* to detect the climatic signal shared by all the sampled trees, and *(ii)* check whether the climate change enhanced common response among trees.

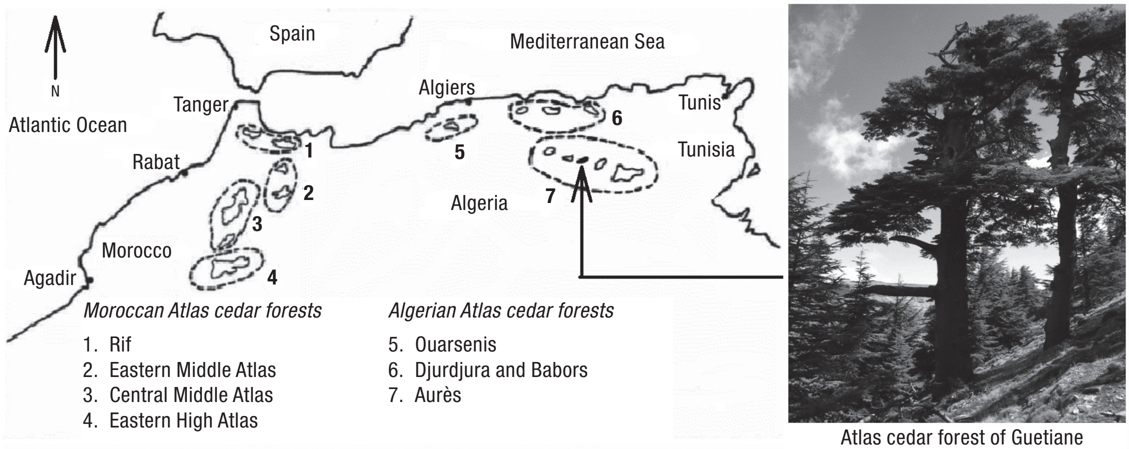
Material and methods

Study site

The Atlas cedar forest of Guetiane is located at about 60 kilometers northwest of the city of Batna, between the Hodna Mountains, of which it forms the eastern part, and the massif of Belezma (Fig. 1). It covers some 300ha (Bentouati, 2008), representing 12% of the total wooded area in the Massif of Guetiane (BNEDER, 2008).

The study area was comprised between the latitudes 35° 41' 34.4" N and 35° 42' 00.052" N and the longitudes 5° 31' 01.6" E and 5° 31' 52.8" E. The elevation ranged from 1,627 m to 1,784 m. The slope was medium to steep (30 and 45%) with a northern to northwestern aspects.

The soil is well-drained and derived from sandstone. The sampled trees grow in more or less pure stands with minor occurrence of *Quercus ilex* and *Juniperus oxycedrus* trees, and in low to medium densities. According to BNEDER (2008), the forest recorded a high mortality rate (60 % to 70%) during the last period of forest dieback, which occurred during the last



Atlas cedar forest of Guetiane

Figure 1. Atlas cedar distribution and study area location. Map redrawn after figure of Mhirit (1999).

decade. However, the phenomenon was intense at lower and medium elevations. In our investigation area, we estimated the level of tree mortality at less than 20%. The different stands are subjected to intensive grazing, compromising natural regeneration of *C. atlantica*. The precipitation is low, with high intra and interannual variability. The Massif of Guetiane receives a total annual precipitation of 350 to 450 mm (ANRH, 1993). According to Gouaref (2012), the annual temperature range is 33°C (m = 0.3°C in January; M = 33.3°C in July). The climate of the region is Mediterranean semi-arid, characterized by a long warm and dry season from May to September and a wet and cold season from October to April (Le Houerou *et al.*, 1977).

Sampling procedure and samples preparation

Twenty Atlantic cedar trees with a healthy trunk were sampled in 2010 using an increment borer. Two cores from opposite sides were taken from each tree, at breast height (1.3 m) and perpendicular to the slope to avoid compression wood. In two extreme conditions (steep slope) only one core per tree was collected. The increment cores were air-dried and mounted in wooden supports. Some twisted cores were softened in a jet of steam and were gently twisted back to the correct alignment. The mounted cores were hand-sanded using a range of grit size from coarse to finer sandpaper until cells were clearly visible under a binocular microscope (Stokes & Smiley, 1996).

Statistical methods

Chronology building

Samples were visually crossdated using a manual skeleton plotting method (Douglass, 1946). Then, the width of each annual ring was measured to the nearest 0.01 mm using a LINTAB tree-ring measurement system and TSAP-Win software platform. Afterwards, the ring width raw data series were checked using the program COFECHA (Holmes, 1983) to confirm crossdating for tree-ring measurements.

ARSTAN for Windows (Cook & Holmes, 1999) was used to standardize the tree-ring width series to remove long-term trends (Cook, 1985). Each individual series of tree-ring widths was fitted with a cubic smoothing spline with a 50% frequency response at 67% of the series length to remove non-climatic trends related to age, size, and the effects of stand dynamics (Cook & Briffa, 1990). The process involved dividing each year's ring width by the year's value of the fitted curve to give a dimensionless index with a mean of one (Fritts, 1976). All the ring-width series were prewhitened to remove non-climate-related persistence and combined using a biweight robust estimate of the mean (Cook, 1985).

The Expressed Population Signal (EPS) was also calculated to test the signal strength in site chronologies (Wigley *et al.*, 1984; Briffa & Jones, 1990). The best series for our investigation was the residual chronology for the time span 1850-2009, with an EPS value above 0.85.

Tree-growth variability

Tree-growth variability was analyzed through trends in temporal evolution of growth index and in years with extreme growth values (mean ± SD). Values over "1 + SD" were considered as wide indices and those below "1 – SD" as narrow indices.

Temporal trends in common variance and mean sensitivity

In order to assess the temporal trend in common variability within the site, principal component analysis (PCA) was computed with all individual residual series for successive 20-year periods lagged 1 year. The variance expressed by the first principal component (PC1) was used as an indicator of the similarity between the chronologies (Andreu *et al.*, 2007). The mean sensitivity (ms_x) was also calculated for each individual tree chronology, considering the absolute relative difference in width from one ring to the next (Fritts, 1976), according to the formula $ms_x = 2|I_{t+1} - I_t|/(I_{t+1}+I_t)$, where I_t and I_{t+1} are adjacent index values. Then, to assess the site mean sensitivity trend, all the series were used to compute an average mean sensitivity as well as its standard deviation (SD_x) over successive 20-year periods lagged 1 year.

Climate-growth interaction

Monthly total precipitation and average temperature from the weather station of Batna were used. This is the longest available dataset from the region. Precipitation data were available from 1930 to 2009. However, temperature data were available only from 1972 to 2009. The program Seascorr (Meko *et al.*, 2011) was used to analyze the seasonal climate signal in tree-ring data. A response function analysis was performed to identify which climate factors are correlated with tree-ring index (Fritts, 1991), determine the season length that affects growth significantly, and to express the relative importance of each monthly climate variable to ring-width index (Fritts, 1976). Besides, additional correlation analyses were computed to establish and plot the monthly climate-growth interaction for each climate variable. The trends in monthly mean temperature and total precipitation, as well as in their variation coefficients (VC) were approached through plotting the slopes of linear regressions fitted on the series of available meteorological data. Then, climate influence on shared growth variability among chronologies and on the mean sensitivity was assessed.

Results

Tree growth variability

The tree-ring index showed high interannual variability through time (Fig. 2). The highest long-term changes in the temporal trend of growth have characterized the last eight decades (1942-2009), and the year 2002 recorded the lowest index. Table 1 confirms this trend. Total growth variance was high, and the highest variance was registered in the last sub-period (1956-2009). Over the 160 analyzed years, 79 years recorded an index value over the mean and 81 years showed an index value lower than the mean, and in both cases the extreme values for the whole series were registered during the last decades. However, a regression analysis showed a significant deviation from the mean only for the plot of lower than the mean indices ($p = 0.000$).

Table 1. Total and sub-period variance of tree-ring index

Period	Variance	SD
1850-2009	0.02967	0.17224
Sub-period 1850-1902	0.01551	0.12455
Sub-period 1903-1955	0.01736	0.13176
Sub-period 1956-2009	0.0565	0.2378

The pointer years (PYs), expressed through the yearly frequency of the individual chronologies with extreme growth indices, are shown in Fig. 3. Of the 160 indices, 62 are normal, 58 are wide and 40 are narrow. However, when considering the PYs registered in at least 25% of the individual chronologies, we recorded 31 wide rings and 30 narrow rings, and when considering PYs registered in at least 50% of the individual chronologies, we recorded 22 wide rings and 25 narrow rings. The PYs show a high variability in

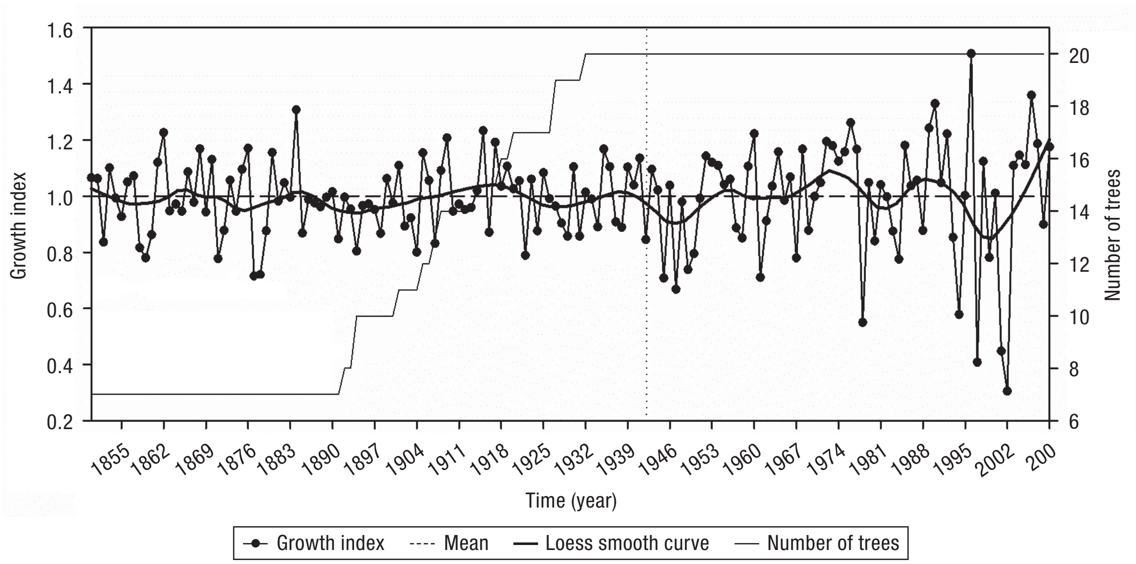


Figure 2. Chronology of index for *C. atlantica* in Guetiane. The trend in tree-ring index is given by the Loess smooth curve (second-order). The vertical dotted line shows the beginning of the highest variability period.

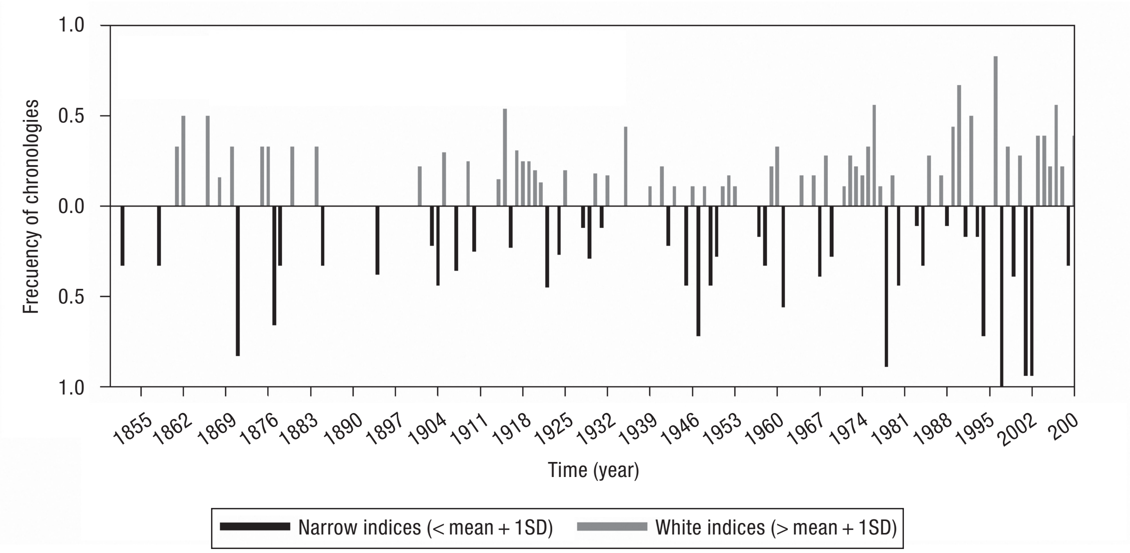


Figure 3. Relative frequency of individual tree chronologies with wide (upward bars) and narrow (downward bars) indices.

occurrence and frequencies over time. Extreme years were most frequently recorded since the 1940s, with higher frequencies among individual chronologies and in occurrence over longer sequences of successive years. The longest period of successive extreme years was recorded from 1996 to 2009, coinciding with the highest frequencies of chronologies.

Temporal trends in common variance and mean sensitivity

Fig. 4 shows the trends of the explained variance of the first three PCs. The PC1 is significant and representing the highest common variance held by the tree chronologies (55.25%). The PC2 (10.05%) and PC3

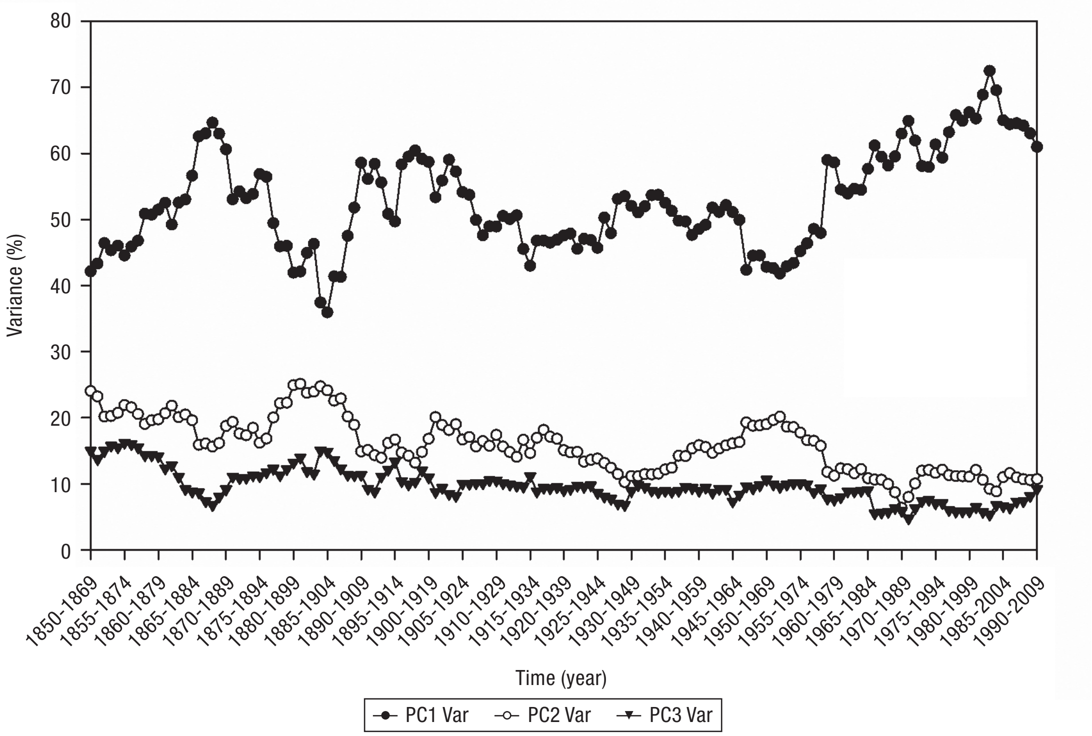


Figure 4. Temporal trend in the variance explained by the three first principal components using subintervals of 20 years lagged 1 year.

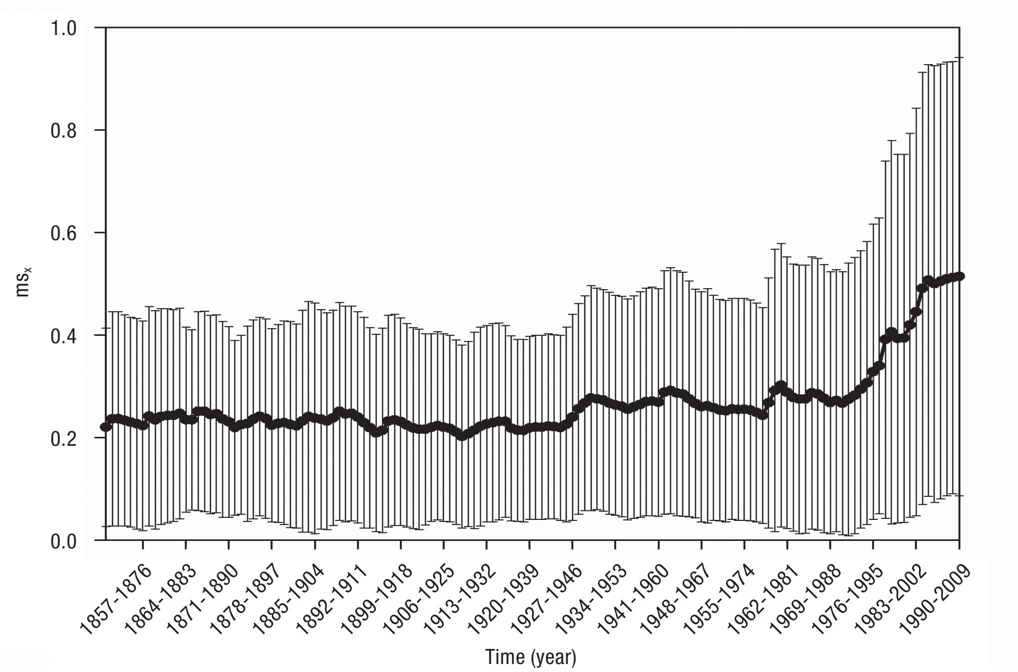


Figure 5. Temporal trend in the mean sensitivity (line) and its standard deviation (bars) using subintervals of 20 years lagged 1 year.

(6.30%) present lower common variances and their temporal trends are opposed to the PC1.

The evolution of the variance explained by the PC1 over time showed a high variability, especially since the middle of the 20th century. A first peak was reached in the late 19th century (interval "1868-1887"), and the most important one was registered at the beginning of the 21st century (interval "1983-2002"). Besides, this shared variance showed a relative continuous increase over the whole last century (last 100-year period). The period 1952-2009 represented the longest interval with significant increase of common variability among tree chronologies (fitted linear regression $R^2 = 0.73$; $p = 0.000$). Moreover, the second half of the 20th century expressed a high and continuous common variance, with an abrupt shift occurred during the earlier period: the variance explained by the first PC increased from 47.92% in the "1958-1977" interval to 58.96% in the "1959-1978" interval. The highest common variance reached a value of 72.48%, recorded within the "1983-2002" interval. After this peak, a relative decrease was observed during the last intervals.

A scan of Fig. 5 reveals relative stability of the mean sensitivity from 1850 to the end of the first half of the 20th century. Then, this trend was interrupted and a substantial increase was observed from the beginning of the 1940s, coinciding with the period of significant increase of tree growth variability (Fig. 2) and of extreme growth years (Fig. 3). The increase in ms_x became more significant in the second half of the 20th century, with an abrupt shift in the late 1970s. From the "1977-1996" to "1978-1997" intervals ms_x increased from 0.34 to 0.39. The maxima were reached in the last intervals, marked by relative stability in both ms_x and SD_x.

Growth climate interaction

Main Seascorr results are shown in Table 2. The correlation of monthly precipitation with tree-ring index increased with increasing length of the averaging period. The highest correlation was obtained in twelve months from prior September to August of the growing year, with a positive and temporal stable correlation from early to late sub-periods. In contrast, the correlation of monthly mean temperature with tree-ring index was negative and decreased with increasing length of averaging period. Current May-June mean temperature yielded the highest correlation. However, this correlation was not temporally stable.

Fig. 6 presents intra-annual correlations of monthly total precipitation and monthly mean temperature with tree-ring index in twelve months from prior September to August of the growing year. Monthly total precipitations are positively correlated with the growth index and are significant from January to June,

Table 2. Highest correlated seasons and temporal stability of correlation of tree-ring index with total precipitation and mean temperature. Common period of available instrumental climate data is 1972-2009. Months preceding the growth year are indicated in capital letters. The correlation is temporally stable when it is significant in both early and late sub-periods

Variable	Season		Pearson correlation		
	Months	Length	Full 1974-2009	Early 1974-1991	Late 1992-209
Precipitation	May	1	0.41**	0.59**	0.34
	Dec-May	6	0.72***	0.68**	0.77***
	Oct-Jun	9	0.78***	0.79***	0.78***
	Sep-Aug	12	0.78***	0.78***	0.79***
Temperature	Jun	1	–0.45*	–0.06	–0.62**
	May-Jun	2	–0.46*	–0.01	–0.68**
	May-Jul	3	–0.43*	–0.09	–0.58**
	Jan-Jun	6	–0.41*	–0.01	–0.66**
	Oct-Sep	12	–0.36	–0.07	–0.59**

Levels of significance are: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

whereas mean temperatures are negatively correlated, and are only significant in May and June.

The slopes of linear regressions fitted on the series of available local climate data were plotted to assess the trends in annual and monthly mean temperature and total precipitation, as well as their variation coefficients (VC) (Fig. 7). Annual and monthly total precipitation showed no significant trend. However, we noticed a significant increase in annual precipitation VC, as well as January, April, May and July precipitation VC. Annual and monthly mean temperature (except winter months) registered a significant increase. In contrast, annual temperature VC, as well as previous September to December, and current February, April and July temperatures VC registered a significant decrease. On the other hand, current May and June, months that showed the highest and significant correlation with the tree-ring index, as well as August, registered an increment in their temperatures VC. However, May was not significant.

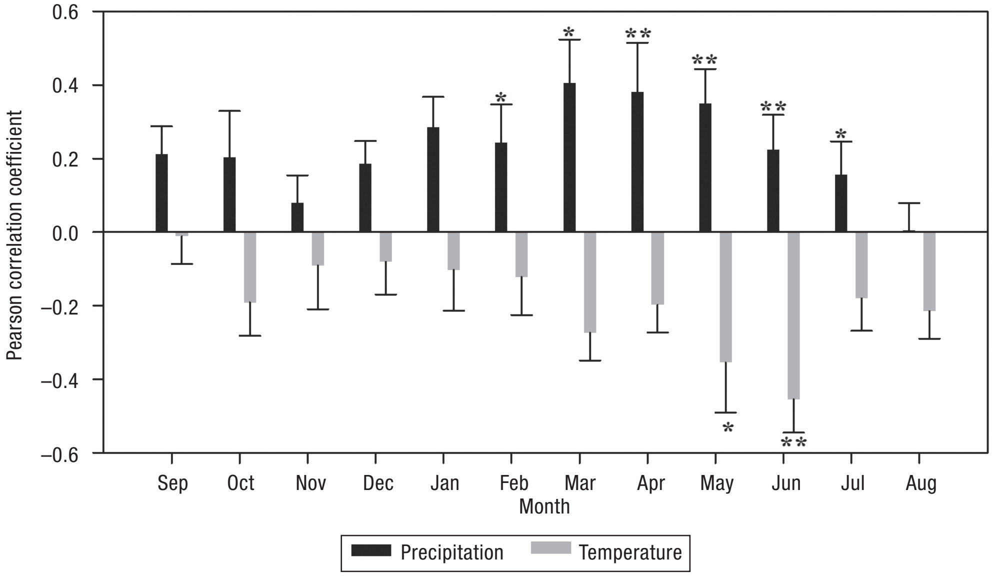


Figure 6. Correlations of monthly total precipitation and monthly mean temperature with tree-ring index in twelve months from prior September to August of the growing year. Months preceding the growth year are indicated in capital letters. * $p < 0.05$. ** $p < 0.01$.

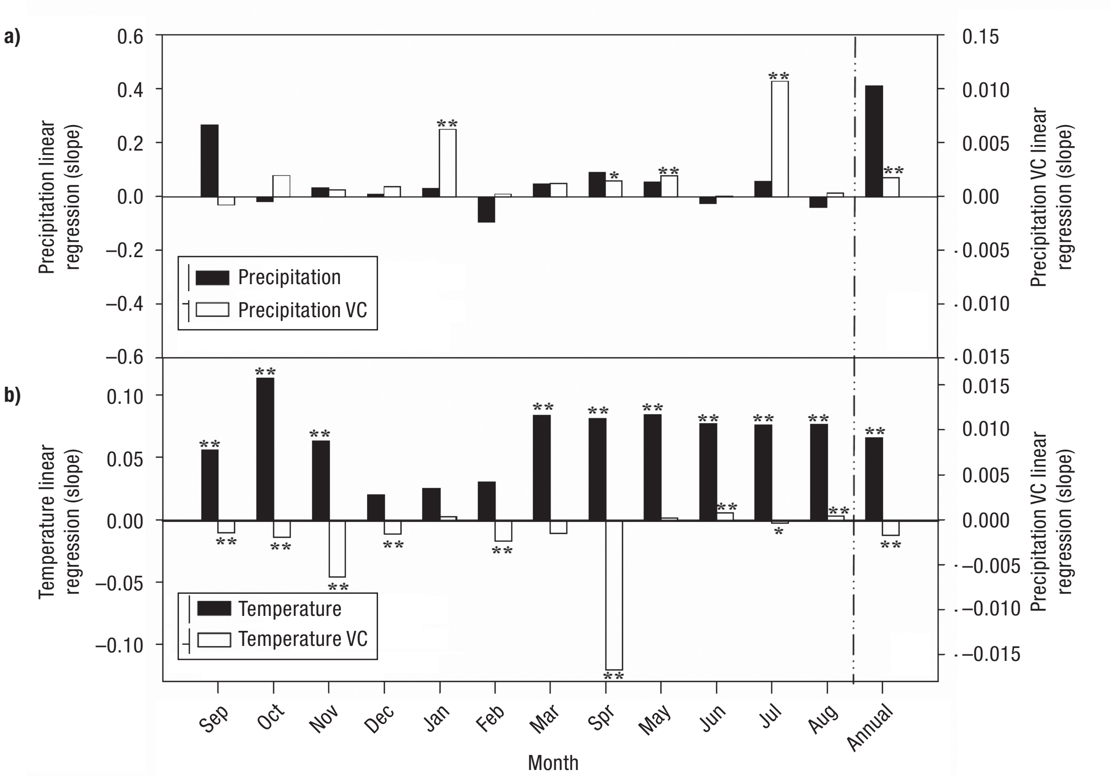


Figure 7. Trends in annual and monthly total precipitation (a) and mean temperature (b) series, as well as their variation coefficients (VC). * $p < 0.05$. ** $p < 0.01$.

Figs. 8 and 9 summarize relationships of previous September to current August total precipitation and current May-June mean temperature, as well as their variation coefficients with common variance and mean sensitivity (only significant relationships are presented). Significant positive correlations between the PC1 variance and previous September to current August precipitation VC (Fig. 8a) and with current May-June mean temperature (Fig. 9a) were found. Mean sensitivity also was positively and significantly correlated to previous September to current August precipitation VC (Fig. 8b), and to current May-June mean temperature (Fig. 9b). However, the relation was significant and negative with May-June mean temperature VC (Fig. 9c).

Discussion

Tree growth variability

Figs. 2, 3, and 4 and Table 1 show that radial growth was highly variable over time. The highest degree of instability was detected from the 1940s onward. This is consistent with the trend in climate variability during the last few decades in the region. Touchan *et al.* (2008a) noticed that the 1940s and the last few decades were periods with substantial and sustained dry conditions.

The chronology registered more pointer years over the last decades, and the increase was only significant in lower than the mean extreme years. This reflects the more limiting climatic conditions that prevailed in the most recent decades, characterized by high variability and frequent severe droughts. This shift towards dry conditions over the last few decades was reported by Kherchouche *et al.* (2012) in the Massif of Aurès (Algeria), Touchan *et al.* (2008b) in Tunisia, Esper *et al.* (2007) and Linares *et al.* (2011) in Morocco, and Touchan *et al.* (2008a, 2010) over northwestern Africa.

Temporal trends in common variance and mean sensitivity

The common variance held by the chronologies was not stable throughout time (Fig. 4). The last century experienced an increase in tree-growth common varia-

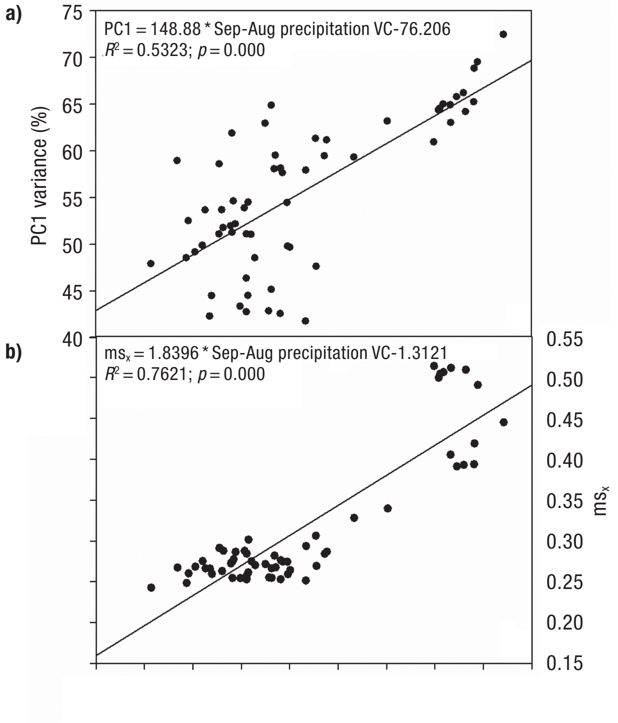


Figure 8. Relationships between September-August precipitation variation coefficient (VC) and (a) the variance explained by the first component (PC1) and (b) the mean sensitivity (ms_x).

bility, which was more pronounced during the last decades. This shared growth variability between tree chronologies can be interpreted as a common response to climatic signals (Tardif *et al.*, 2003). The highest common variance among the chronologies, recorded during the last few decades, shows that trees were growing more synchronously under more limiting climate conditions to growth. Andreu *et al.* (2007) related a common variability shared by 38 chronologies across the Iberian Peninsula to macroclimate. Macias *et al.* (2006) considered the changes in shared growth variability in the silver fir forests of northeastern Iberian Peninsula over the 20th century as a signal of climatic changes, which have affected the growth of the forest.

A first peak in the common variability was observed at the end of the 19th century, coinciding with extreme climate conditions. Touchan *et al.* (2008a) pointed up a six-year period, from 1876 to 1881, where every consecutive year was below the long-term reconstructed index mean in northwestern Africa. Boudy (1950) in Abdsemed (1981) reported that an exceptional drought could have occurred between 1875 and 1880, which could have destroyed many stands of Atlas cedar in the Aurès region. Lapie (1909) reported that during some severe winters, especially those of 1879 and 1880, dieback of entire stands of Atlas cedar was observed in the Aurès region and in Kabylia. Le Houerou (1980) noticed that in 1881 Algerian forests lost 169,000 ha because of wildfires associated to drought events. The same year recorded some of the most catastrophic fires Algeria has ever experienced (Meddour-Sahar *et al.*, 2008).

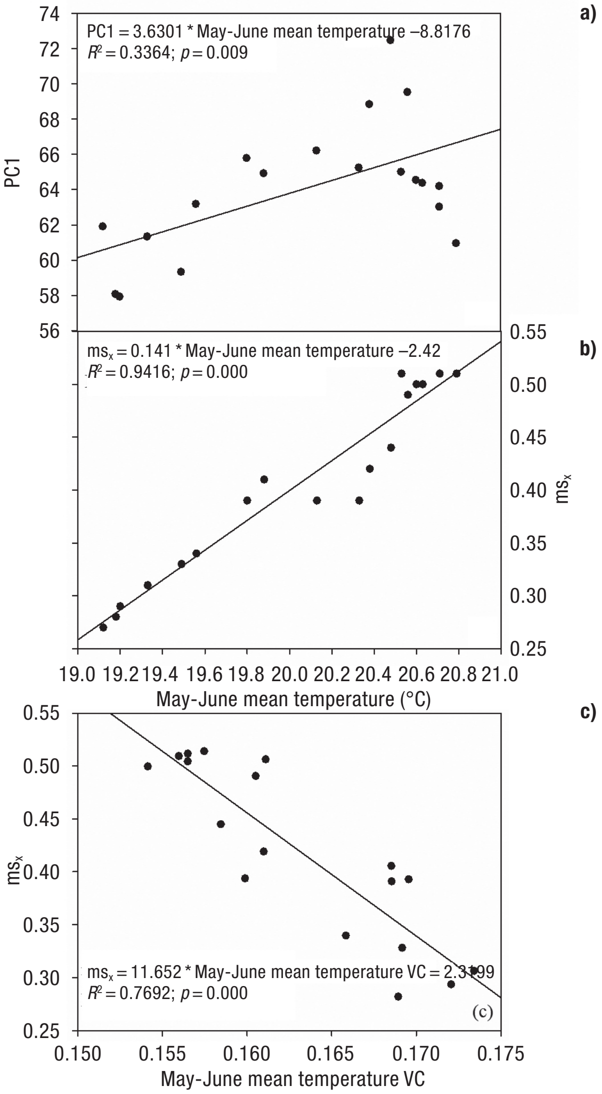


Figure 9. Relationships between May-June mean temperature and (a) the variance explained by the first component (PC1) and (b) the mean sensitivity (ms_x), and (c) between May-June mean temperature variation coefficient (VC) and the mean sensitivity (ms_x).

The shift reported at the end of the 1970s was due to dramatic changes in climate conditions. Through a global documented investigation in diverse forest types and climatic zones in the world, Allen *et al.* (2010) showed that forest mortality met the criteria of events that were driven by climatic water/heat stress since 1970. This provoked an abrupt increase in shared growth variability and generated a very high narrow ring frequency of the chronologies in 1978 (Fig. 3). According to Abdsemed (1981), droughts that prevailed in 1977 and 1978 in the Aurès Massif dried out even *Quercus ilex*, which is reputed for its drought-hardiness, and could have caused the dieback that occurred within *C. Atlantica* forests at the beginning of the 1980s. Suggesting a dendrochronological study, the author put forward the idea of a probable millennium drought. The trend in PC1 variance confirms the two periods of droughts of the late 1870s and late 1970s. However, in their dendrochronological approach to drought impact on *C. atlantica* forest dieback in the Aurès, Kherchouche *et al.* (2012) reported another exceptional drought event of 4 years' duration in the second half of the eighteenth century, but with a time-gap of some ten years, from 1765 to 1768. Furthermore, over northwestern Africa, Touchan *et al.* (2008a) reported a six-year period of drought from 1770 to 1775. Kacha (1990) in Meddour-Sahar *et al.* (2008) noticed that six years of drought, with variable intensities throughout different regions, were registered all over Algeria in the 1980s. Our results corroborate these reports: 1978, 1980, 1983, 1984 and 1988 registered PYs with a narrow ring. The highest shared growth variability among individual series was recorded in the interval ending with the year 2002 (1983-2002). The year 2002 recorded a deficit in previous September to current August total precipitation and a high May-June mean temperature. Touchan *et al.* (2008a) showed that the one set severe drought of 1999-2002 appears to be the worst in northwestern Africa since the middle of the 15th century. This event triggered substantial mortality even in other Algerian tree species, including *Pinus halepensis*, *Quercus ilex*, *Quercus suber*, *and Juniperus thurifera* (Allen *et al.*, 2010). After the year 2002, the common variability remained high but showed a slight decrease coinciding with a significant decrease in *C. atlantica* dieback rate in the region.

A shift towards more sensitive trees to climate variation was observed in the middle of the second half of the 20th century, indicated by abrupt increases in both ms_x and SD_x (Fig. 5). Andreu *et al.* (2007) reported similar trend in the northwestern Iberian Peninsula. The trends in ms_x and SD_x ended with a maximum and relative stability during the last decade, indicating that even after the period of high forest dieback, tree growth was still influenced by high climate variability. In north Morocco, Linares *et al.* (2011) reported an increase in drought events and temperature since the 1970s, and noticed consistent growth declines and increased drought sensitivity in *C. atlantica* stands since the early 1980s.

According to Lenton *et al.* (2008), the substantial increase in mean sensitivity that began in the 1940s can be seen as a warning signal of an approaching tipping point, expressed here by the shift mentioned at the end of the 1970s. Hence, the mentioned periods of forest dieback that occurred during the last few decades can be considered a tipping element, reflecting the regional-scale feature of the climate that would have exhibited a threshold behavior in trees response to climate change.

Coincidence in trends in growth variability, in common variance between tree chronologies and in mean sensitivity over time suggests an evolution towards more common response to climate condition.

Growth-climate interaction

Growth-climate relationships were established between the residual tree-ring series and local instrumental data (Fig. 6). The results showed a positive long-term and cumulative effect of precipitation, and a negative and immediate effect of temperature. Tree-growth is influenced by total precipitation from previous September to current August with significant January to June totals. As regards mean temperature, the correlation was not temporally stable and was only significant in a period of two months, current May-June. This reflects the key role of precipitation on growth control. Indeed, by selecting trees growing at their altitudinal and latitudinal range limits, it is possible to maximize particular ecological factors in the tree rings. Trees growing near northern or upper timberlines contain most information on temperature, while those growing near the lower-elevation, arid timberline provide more information on precipitation (Pilcher, 1990).

The last decades have registered a significant positive increase in annual as well as January, April, May and July precipitation VC, whereas annual and monthly total precipitations did not show any significant trend

(Fig. 7). Thus, tree growth is primarily controlled by precipitation variability. The negative significant correlation between mean sensitivity and current May-June mean temperature VC (Fig. 9c) did not match the trends of the plotted slopes of linear regressions fitted on the series of temperature VC (Fig. 7) and the mean sensitivity evolution through time (Fig. 5), confirming the status of temperature as a secondary climate variable. Globally, trends in Figs. 8 and 9 show that the increases in shared variance and mean sensitivity were mainly controlled by the increment in previous September to current August precipitation variability (VC).

A monthly total precipitation analysis revealed a very high uneven intra- and inter-annual distribution of rainfall. Many years registered rainfall defeciency during winter and spring months, periods in which significant correlations with the growth index were mentioned. In many cases high rainfall totals were reported in form of storms with months that recorded more than two to three times the mean total precipitation. During such years, water availability to trees, then to growth, did not correspond with the total annual rainfall, which means that those precipitations were not efficient. We assume that overstory cover reduction, due mainly to the different periods of forest dieback, would certainly have caused an increase in runoff and decreased infiltration and soil water storage, especially in case of storm precipitation. The effects of land-cover changes have recently been associated with persistent predictions of warming and drying trends throughout the Mediterranean Basin (Rotenberg and Yakir, 2010). Consequently, during periods of frequent storms, there were years in which the growth index was low while total precipitation was largely higher than the mean. Besides, years with high temperature and high and/or more or less efficient total precipitation did not show narrow indices. Globally, high growth indices were associated with high rainfall and/or its efficiency, and narrow rings coincided with high temperature only when precipitation was low or non-efficient.

Conclusions

Our findings showed a high variability in tree growth between 1850 and 2009. The highest degree of variability was recorded during the last decades, consistently with a very high climate variability trend, leading to an increase in the number of pointer years. As the region experienced more frequent and severe droughts, a significant increase in the pointer years with narrow rings was observed. These more limiting conditions generated a higher common response of tree growth towards climatic signals.

Growth-climate relationships showed a significant positive, cumulative and stable temporal effect of precipitation variability. May-June mean temperature and May-June temperature variability showed a significant negative correlation with the tree growth variability, but the correlation was not stable over time.

Further studies at larger spatial and temporal scales, with a high number of sites, and involving different species would highlight the micro-, meso- and macroclimate variability effect on tree-growth in the whole region.

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