Trees (2012) 26:443–458
DOI 10.1007/s00468-011-0605-3

ORIGINAL PAPER

Araucaria araucana tree-ring chronologies in Argentina: spatial growth variations and climate influences

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Received: 16 April 2011 / Revised: 5 August 2011 / Accepted: 9 August 2011 / Published online: 25 August 2011

Abstract Seventeen tree-ring chronologies from the conifer *Araucaria araucana* (Molina) K. Koch have been analyzed across its range of distribution in Argentina. We studied the growth patterns and determined the main climatic factors influencing *A. araucana* radial growth. All the chronologies show a strong common signal observed by the high amount of variance explained by the first principal component (PC1) and the high mean correlation ($r = 0.597$) between the chronologies over the 1676–1974 interval. On this basis, we developed a regional chronology that is 866 years long (A.D. 1140–2006) and includes 621 tree-ring series. Based on the PC2 scores, chronologies were clearly separated by elevation in high- and low-elevation records. Regional tree growth is strongly negatively related to temperatures during summer and fall in the previous-growing season and spring in the current-growing season, respectively. A positive association of tree growth with precipitation is recorded during spring in the current growing season. These results suggest a close relationship between *A. araucana* tree growth and water availability on a regional scale. This observation is also consistent with a positive and significant correlation between our *A. araucana* regional record and a reconstruction of November–December rainfall for northern Patagonia inferred from the xeric *Austrocedrus chilensis* during the past 400 years. Negative correlations between *A. araucana* regional growth and the sea surface temperature in the Niño 3.4 region reflect the occurrence of above-mean summer temperatures in the region during positive tropical Pacific SST anomalies. The negative relationship with the Antarctic Oscillation (AAO) results from reduced precipitation in our study region during the positive phase of the AAO. The effect of elevation on water availability is consistent with significant correlations between ring-width variations at lower elevations and the Palmer Drought Severity Index during spring and summer in the current growing season. Our study emphasizes the high dendroclimatological potential of *A. araucana* chronologies for reconstructing past climate variations in northern Patagonia during the past millennium.

Keywords Growth patterns · PCA · Northern Patagonia · ENSO · AAO · PDSI

Communicated by S. Leavitt.

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Introduction

Tree-ring analysis is one of the most powerful tools for the study of environmental changes and the identification of fundamental relationships between tree growth and climate (Cook and Pederson, 2011). Dendrochronology can produce long, annually resolved records of past climate, and Patagonia is home to several long-lived tree species used for dendroclimatic reconstructions (Boninsegna et al. 2009). As climate is the major environmental factor influencing tree growth throughout Patagonia on long spatial scales, the pattern of interannual variations in ring widths is often similar among trees across the whole region (Boninsegna et al. 2009). The long-lived conifer *Araucaria araucana* (Molina) K. Koch provides a great opportunity for studying climate-growth relationships in northern Patagonia and to gain insights into the spatial and temporal patterns of growth variability across the region.

The first dendrochronological sampling of *A. araucana* forests was carried out in 1949 and 1950 by a group led by Professor E. Schulman from the Laboratory of Tree-Ring Research at the University of Arizona. Based on his study of the cores collected and ring counts in some logs at a sawmill in Curacautín, Chile, Schulman (1956) recognized the dendroclimatic potential of *A. araucana*, associated with its longevity (nearly 1,000 years) and the particular type of environments where the species grows. However, he pointed out potential difficulties of tree-ring visualization in *A. araucana* based on its anatomical properties.

Studies were not resumed until the 1970s (1973–1978) when sampling was undertaken by dendrochronologists from Tucson, led by Dr. V. LaMarche Jr. and Argentinean collaborators from IANIGLA in Mendoza. During these campaigns, 17 sites were explored and the first 12 chronologies of *A. araucana* were developed (LaMarche et al. 1979). However, the final project report only presented the chronologies and their statistics without making any statistical comparison with climate variables. The first river flow reconstruction in Argentina was carried out using five of these chronologies by Holmes et al. (1979). Villalba et al. (1989) developed the first reconstruction of summer temperatures (1500–1974) using eight of the LaMarche et al. (1979) chronologies. Villalba (1995) presented the first systematic examination of the relationships between *A. araucana* growth, temperatures and precipitation. Based on four Argentinean and two Chilean chronologies, he used correlation and response functions to show an inverse relationship between *A. araucana* radial growth and previous summer temperatures. However, relationships between radial growth of *A. araucana* and rainfall were not directly established (Veblen et al. 1995; Villalba 1995).

The need for developing millennium-long climate reconstructions in the Southern Hemisphere (IPCC 2007) has renewed the interest of the international tree-ring community on the *A. araucana* records from the northern Patagonian Andes. *Araucaria araucana* distribution ranges from the high-elevation Andes Mountain with more than 2,000 mm year^{-1} to the relatively-lower basaltic plateaus in the steppe border with less than 500 mm year^{-1}. Differences in the response of *A. araucana* to climate are expected to occur along this marked precipitation gradient. The development of new, additional tree-ring chronologies of *A. araucana* in Argentina might provide a unique opportunity to properly characterize the responses of this species to climate as well as to identify differences in the relationships with climate along its distribution area. Therefore, the objectives of this study are (1) to develop a network of *A. araucana* chronologies and analyze their growth patterns over its distribution in Argentina, (2) to explore the spatial variations in *A. araucana* tree-growth response to temperature and precipitation and finally (3) to examine possible relationships between this radial growth variability and regional climate forcings.

Materials and methods

New tree-ring collections

Collections of *A. araucana* in Argentina were undertaken during four austral summers (2005 through 2008). New collections east of the Andes continental divide between 37°50′ and 39°37′S yielded ten new chronologies (Table 1; Fig. 1). Original tree-ring measurements from seven chronologies of *A. araucana* developed by LaMarche et al. (1979) and Villalba et al. (1989) were downloaded from the ITRDB.[1]

Most of the *A. araucana* trees were sampled in stands located on rocky sites on the slopes of the Patagonian Andes. Sampling sites were selected on stable substrates with no evidence of fire activity. Only the Nahuel Mapi site shows evidence of logging as a few stumps were observed close to the sampled stand. *Araucaria araucana* was an important timber tree during the first half of the twentieth century. Nowadays, *A. araucana* is protected by local legislation and CITES.[2] Elevation, slope, aspect, mean annual temperature and annual precipitation for each site are presented in Table 1. Both climatological variables were obtained from Worldclim Global Climate Data (http://www.worldclim.org/).

Two to four cores were collected at breast height from each of 30 trees at each site in order to facilitate crossdating of samples and strengthen the common signal in the chronologies (Fritts 1976). Based on previous experience (Schulman 1956; LaMarche et al. 1979), our sampling strategy consisted in taking cores from dominant trees, but not only from old trees. In this way, our collections incorporate trees with different ages, so the youngest trees helped us visualize growth patterns that were difficult to date in recent decades.

[1] The International Tree-Ring Data Bank (ITRDB) held at the World Data Center for Paleoclimatology website (NOAA Paleoclimatology Program, http://www.ncdc.noaa.gov/paleo/treering.html).

[2] Convention on International Trade in Endangered Species of Wild Fauna and Flora.

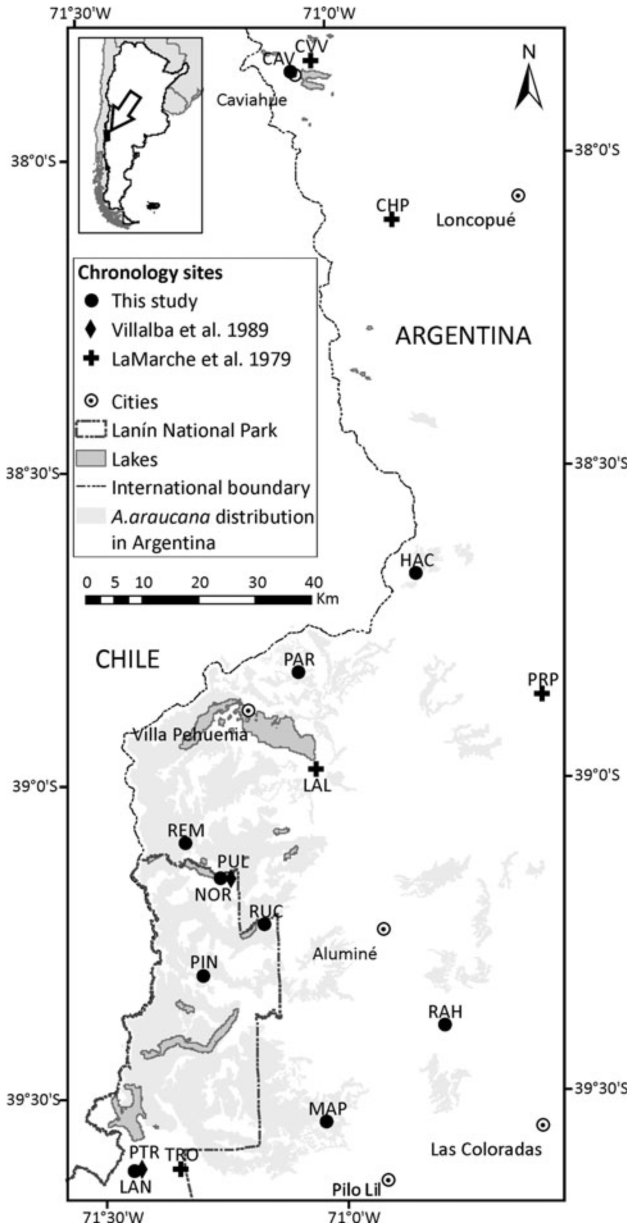

Fig. 1 Map showing sample sites for the tree-ring chronologies

Chronology development

Standard dendrochronological procedures (Fritts 1976; Cook et al. 1990) were used to develop the new chronologies listed in Table 1. Cores were mounted and sanded following Stokes and Smiley (1968) and visually crossdated using the list method (Yamaguchi 1991). Following Schulman's convention (1956) for the Southern Hemisphere, annual rings were assigned to the year in which ring formation started. Ring widths were measured to the nearest 0.001 mm, and the computer program COFECHA (Holmes 1983) was used to detect measurement and crossdating errors.

Each tree-ring width record was standardized and then averaged with the other tree-ring series to produce a mean chronology for each site (Fritts 1976; Cook et al. 1990). Standardization involves fitting the observed ring-width series to a curve or a straight line and computing indices from the measured ring widths divided by the expected value. This reduces variance among cores and transforms ring widths into dimensionless indices. Standardization also removes or reduces the influences of disturbance and the tree's biological growth trend on ring widths (Fritts 1976).

Standard and residual chronologies from the previous and new collections were produced by the ARSTAN 4.0c program (Cook 1985). Tree-ring measurements were detrended using negative exponential curves and linear regressions with negative or zero slope. Residual chronologies were produced in the same manner as the standard chronologies, but in this case the chronologies were residuals from autoregressive modeling of the standardized index series. Residual chronologies are used in dendroclimatic studies because the removal of serial autocorrelation is required for some statistical analyses (Villalba and Veblen 1997). Although residual chronologies were used in all statistical analyses, standard chronologies are shown in the figures to facilitate the visualization of long-term trends in the tree-ring records.

The quality of the chronologies was assessed on the basis of the following statistics: mean sensitivity (MS), the average correlation between all series (RBAR), the expressed population signal (EPS) and the first-order autocorrelation. Mean sensitivity represents a measure of the interannual variability in tree rings (Fritts 1976), whereas the RBAR is a measure of the common variance between the single series in a chronology (Wigley et al. 1984). Running RBAR illustrate changes in the strength of common patterns of tree growth over time. EPS measures how well the finite-sample chronology compares with a theoretical population chronology based on an infinite number of trees (Wigley et al. 1984). The cutoff point for accepting EPS suggested by Wigley et al. (1984) is 0.85. The RBAR and EPS values were computed using a 50-year moving window with a 25-year overlap. First-order autocorrelation is a measure of the association between growth rings in two consecutive years.

The similarity between the residual chronologies (and hence the detection of intra-regional differences) was analyzed using principal component analysis (PCA; Cooley and Lohnes 1971) and correlation analysis. Residual chronologies were used to avoid inflating the correlation coefficients due to serial autocorrelation present in tree-ring series. PCA has been used in dendrochronology for the ordination and classification of trees, chronology sites or response functions for individual series (Peters et al. 1981)

Table 1 Site characteristics of the tree-ring chronologies

Site	Code	Latitude S	Longitude W	Elevation (m)[a]	Slope (°)[a]	Aspect[a]	Mean annual tmp (°C)[b]	Annual pp (mm)[b]	Source[c]
Caviahue LaMarche	CVV	37°50'54.2"	71°01'44.8"	1674	7	SE (126°)	7.5	1035	L1979–ITRDB
Caviahue	CAV	37°51'54.2"	71°04'08.9"	1695	17	N (10°)	7	1046	This study
Chenque Pehuén	CHP	38°06'00.0"	70°51'00.0"	1616	8	NE (54°)	7.8	865	L1979 - ITRDB
Pino Hachado	HAC	38°40'15.1"	70°50'14.6"	1622	33	N (324°)	7	712	This study
Paso del Arco	PAR	38°49'32.4"	71°04'49.2"	1697	19	E (74°)	7	896	This study
Primeros Pinos	PRP	38°53'00.0"	70°37'00.0"	1613	12	NE (37°)	7.7	474	L1979—ITRDB
Lonco Luan	LAL	38°59'00.0"	71°03'00.0"	1164	8	W (290°)	9.1	827	L1979—ITRDB
Remeco	REM	39°05'42.5"	71°19'14.5"	1217	23	W (289°)	8.4	1098	This study
Ñorquinco	NOR	39°09'08.1"	71°14'56.6"	1142	13	N (347°)	7.8	961	This study
Ea. Pulmarí	PUL	39°08'35.1"	71°11'40.8"	1084	5	N (356°)	8.8	917	V1989 -ITRDB
Rucachoroi	RUC	39°13'39.3"	71°09'46.0"	1317	9	E (88°)	7.3	811	This study
Pinalada Redonda	PIN	39°18'26.9"	71°17'22.6"	1119	16	N (348°)	8.4	955	This study
Rahue	RAH	39°23'39.5"	70°47'43.6"	1455	4	SW (231°)	7.2	500	This study
Ea. Nahuel Mapi	MAP	39°32'46.8"	71°02'37.0"	1531	5	SE (116°)	6.8	639	This study
Lago Tromen	TRO	39°36'54.7"	71°20'47.0"	965	2	E (71°)	8.7	969	L1979 - ITRDB
Lanín	LAN	39°36'58.5"	71°26'33.4"	1565	16	N (12°)	5.5	985	This study
Paso Tromen	PTR	39°37'20.0"	71°25'24.6"	1472	9	NE (47°)	6.5	984	V1989 - ITRDB

[a] Elevation, slope and aspect are derived from a digital terrain model (SRTM) with 90 m resolution

[b] Mean annual tmp (temperature) and annual pp (precipitation) from Worldclim Global Climate Data (1-km gridded raster, resampled to 90 m with nearest neighbor method)

[c] ITRDB, International Tree-ring Data Bank; L1979, LaMarche et al. (1979); V1989, Villalba et al. (1989)

or chronologies (Villalba and Veblen 1997). To show the geographical variation in tree rings throughout the *A. araucana* distribution in Argentina, the relative weights (eigenvectors) of each chronology for the principal components were plotted as maps in their geographic position using the program Surfer 8 (Golden Software 2002). Isolines of eigenvectors were calculated using the kriging interpolation procedure (Golden Software 2002).

Climatic influences on *A. araucana* growth

Correlation functions (Blasing et al. 1984) were used to determine the influence of climatic factors on the growth of *A. araucana*. Correlation functions between the residual tree-ring chronologies and different climatic variables (temperature, precipitation, Palmer Drought Severity Index, sea surface temperature from the Niño 3.4 region, Antarctic oscillation index) were computed for a 7-quarter period started with spring (September–November) of the previous growing season to fall (March–May) at the end of the current growth year.

Regional temperature and precipitation records were developed by averaging monthly data from climate records in the region (Table 2). The average monthly departures for each site were computed by subtracting the common period site monthly mean from the value for each month (temperature common period: 1966–1973 and precipitation common period: 1951–1975) and dividing the result by the standard deviation for each site. These monthly departures were then averaged across the sites. As a consequence of using normalized departures, each station, independent of its particular values of temperature and precipitation, has the same weight in the averaged regional records.

The Palmer Drought Severity Index (PDSI; Palmer 1965) takes into account precipitation, evapotranspiration and soil moisture conditions, all of which are determinants of hydrologic droughts. The PDSI is a standardized measure of surface moisture conditions [ranges from about -10 (dry) to $+10$ (wet)], which allows comparisons across regions and time. In this study, the PDSI monthly series for the study area (1902–2005) was derived from the Dai et al. (2004) $2.5° \times 2.5°$ gridded data set (central point: 38°45′S and 71°15′W).

El Niño-Southern Oscillation (ENSO) is a coupled ocean–atmosphere phenomenon rooted in the tropical Pacific, characterized by irregular fluctuations between its warm (El Niño) and cold (La Niña) phases with a periodicity ranging from 2 to 7 years (Diaz and Markgraf 2000). Rainfall and temperature anomalies associated with occurrence of the El Niño and La Niña events are the major source of interannual variability over much of South America (Ropelewski and Jones 1987; Aceituno 1988; Garreaud et al. 2009). To assess the relationships between

Table 2 Meteorological records used for comparing tree growth with climatic variation

Station	Latitude S	Longitude W	Elevation (m)	Record period	Parameter	Source
Buta Ranquil	37°00’	70°07’	1250	1966–2005	T	SSRH
Las Lajas	38°31’	70°22’	713	1916–1973	T	SMN
Flor del Lago	39°20’	72°01’	300	1931–1961	P	KNMI
Ea Mamuil Malal	39°39’	71°14’	990	1935–1998	P	HIDRONOR
Ea Collun-co	39°58’	71°12’	875	1912–1989	P, T	HIDRONOR
San Martín de los Andes	40°10’	71°22’	650	1936–1975	P	HIDRONOR
Bariloche	41°09’	71°16’	825	1951–2009	P, T	SMN

P, monthly precipitation; T, mean monthly temperature, SSRH, Subsecretaría de Recursos Hídricos de la Nación (Argentina); SMN, Servicio Meteorológico Nacional (Argentina); HIDRONOR, Hidroeléctrica Norpatagónica S.A.; KNMI, Royal Netherlands Meteorological Institute

Table 3 Descriptive statistics for the 17 *A. araucana* chronologies considered in this study (see Table 1 for chronology code definitions)

Code	Record period	Raw data		Standard chronologies	
		RW (mm)	Mean sensitivity	Mean RBAR	Autocorrelation[a]
CAV	1550–2003	0.646	0.195	0.208	0.563
CVV	1444–1974	0.858	0.192	0.248	0.699
CHP	1246–1974	0.569	0.205	0.241	0.642
HAC	1424–2006	0.810	0.172	0.208	0.606
PAR	1264–2006	0.773	0.229	0.299	0.750
PRP	1140–1974	0.603	0.228	0.237	0.706
LAL	1306–1974	0.903	0.220	0.211	0.623
PUL	1589–1989	0.865	0.232	0.328	0.502
REM	1450–2006	0.852	0.195	0.188	0.691
NOR	1676–2006	0.939	0.187	0.215	0.726
RUC	1647–2006	0.913	0.194	0.232	0.645
PIN	1606–2006	1.018	0.230	0.215	0.591
RAH	1591–2006	1.323	0.184	0.223	0.601
MAP	1525–2006	1.001	0.194	0.209	0.569
TRO	1617–2006	1.180	0.205	0.250	0.602
PTR	1385–1983	0.883	0.204	0.226	0.537
LAN	1291–2006	0.584	0.222	0.256	0.566

RW, Mean ring width, Mean RBAR, mean correlation between series

[a] Autocorrelation, serial correlation coefficient for the chronology at a lag of 1 year (i.e., the first-order autocorrelation)

ENSO and *A. araucana* growth, we used the sea surface temperatures (SSTs) from the Niño-3.4 region (Trenberth and Stepaniak 2001).[3]

The Antarctic Oscillation (AAO), also known as the Annular Mode in the Southern Hemisphere (SAM), is the dominant pattern of variability in the tropospheric circulation south of 20°S, and it is characterized by pressure anomalies of one sign centered on the Antarctic and anomalies of opposite sign in the circum-hemispheric band at 40–50°S (Thompson and Wallace 2000). The positive phase of AAO is associated with a decrease in surface pressure and geopotential heights over Antarctica and a strengthening and poleward shift of the Westerlies (Garreaud et al. 2009). Opposite conditions prevail during the negative phase. During positive phases of the AAO there is a marked decrease in rainfall in northern and central Patagonia and increased precipitation during negative phases (Aravena and Luckman 2009). To assess the relationships between the AAO and *A. araucana* growth, we used the AAO index based on the principal component of the geodynamic height anomalies of 850 hPa south of 20°S for the period 1948–2002 (Thompson and Wallace 2000).[4]

[3] The Niño 3.4 region is the tropical Pacific extending from 5° N to 5° S, and from 170° to 120° W). We used the updated series available from the website of the Global and Climate Dynamics of the National Centre for Atmospheric Research (http://www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/index.html).

[4] The series available from the website of the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) of the University of Washington was used (http://jisao.washington.edu/data/aao/).

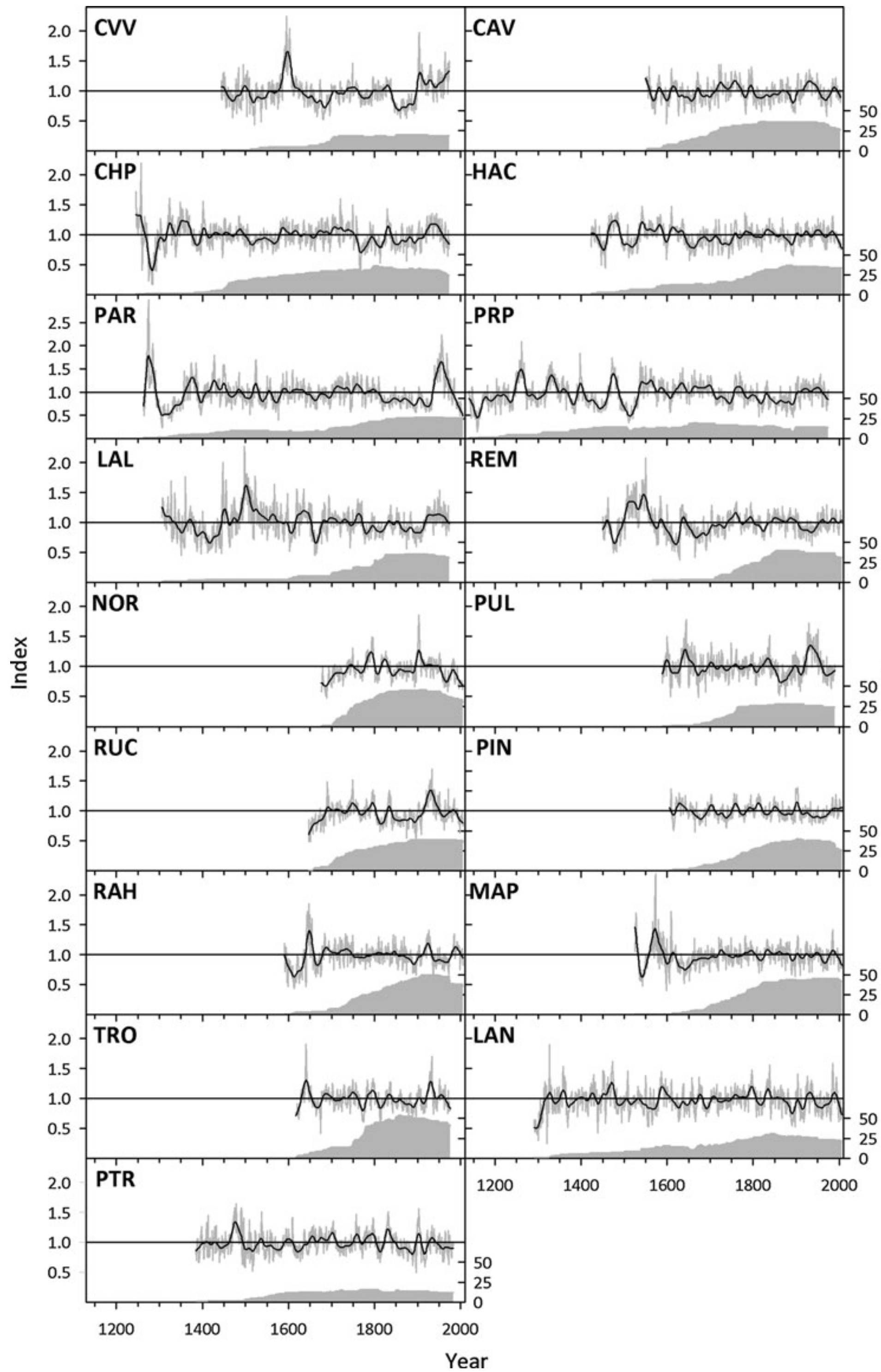

Fig. 2 *A. araucana* standard chronologies (*gray curves*). The *black lines* are a 25-year spline. Sample size shown as the *shaded gray* areas (see Table 1 for chronology code definitions)

Results

Characteristics of the chronologies and intra-regional variations

As described by Schulman (1956) and Tortorelli (1956), the latewood color in *A. araucana* is not pronounced and this band is commonly not narrower than the earlywood. The precise determination of annual-ring boundary is difficult on even young, fast-growing trees and often quite impossible on the last segments of old trees with slow growth. Consequently, the most recent decades in many series could not be dated.

The statistics for the tree-ring chronologies are shown in Table 3. The mean annual increment (MAI) varies from

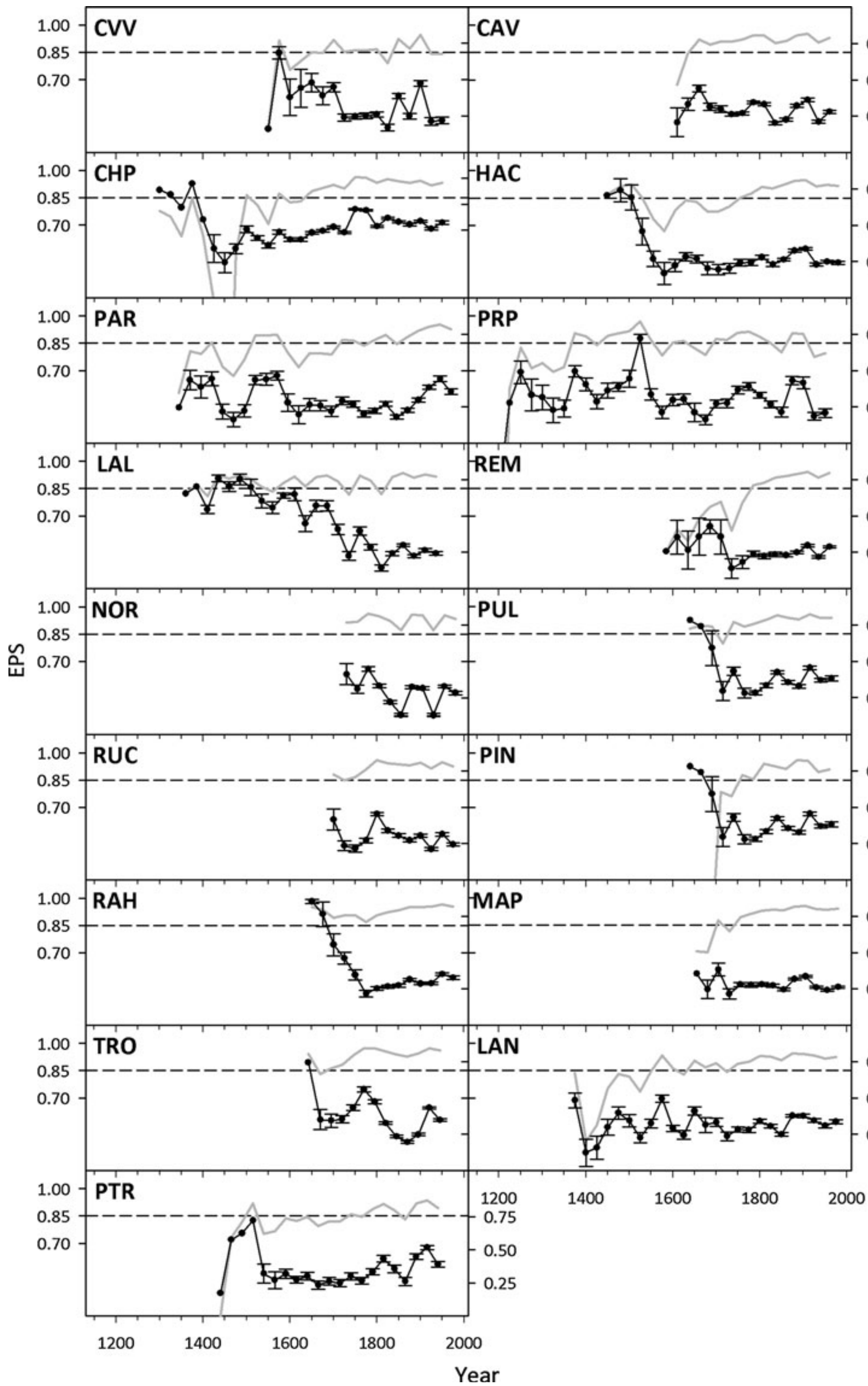

Fig. 3 Running EPS (*gray curves*) and RBAR (*black curves* with ±standard errors) for each *A. araucana* standard chronology (see Table 1 for chronology code definitions)

0.569 to 1.323 mm year^{-1} in Rahue and Chenque Pehuén, respectively. The mean sensitivity varied between 0.172 and 0.232 (in Pino Hachado and Ea. Pulmarí, respectively). The longest chronology is from Primeros Pinos and covers the period 1140–1974 (Table 3 and Fig. 2).

High values of first-order autocorrelation were observed in all chronologies. The mean RBAR values ranged between 0.188 and 0.328 (Table 3). The intra-chronology correlations (running RBAR, Fig. 3) are variable over time. The longest chronologies run below the 0.85 EPS threshold in their earliest portions (Fig. 3), mainly due to the low sample replication.

In the PCA of the residual tree-ring chronologies over their common period (1676–1974), the three first factors

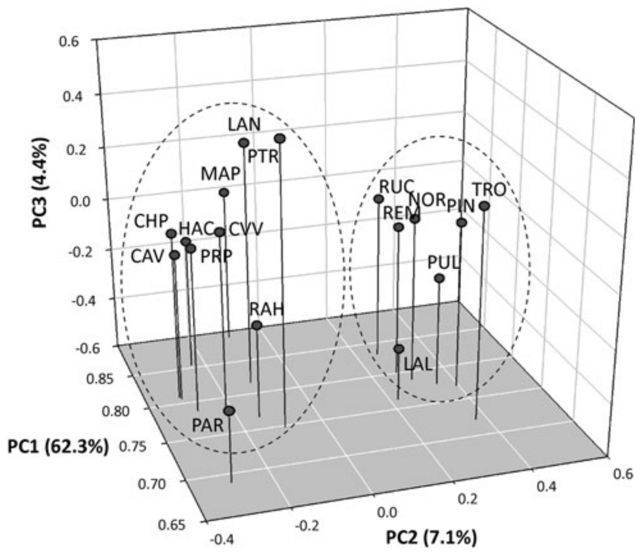

Fig. 4 Relative positions of 17 residual chronologies of *A. araucana* according to the three most important axes resulting from a PCA. The percentage of total variance associated with each PC is indicated in parenthesis. Ellipses identify the two major groups of chronologies

accounted for 62.3, 7.1 and 4.4% of the total variance, respectively, or cumulatively for 73% of the total variance (Fig. 4). The first component showed high common interannual variability across this network, and consequently, it did not provide a clear way of separating chronologies by differences in site conditions. Differences in tree-growth variations only became evident when the second component (PC2) was considered. Opposite trends were observed in two groups of chronologies (Fig. 4). The Caviahue-LaMarche, Caviahue, Chenque Pehuén, Pino Hachado, Paso del Arco, Primeros Pinos, Rahue, Ea. Nahuel Mapi, Paso Tromen and Lanín chronologies all had negative factor loadings in the PC2. In contrast, Lonco Luan, Remeco, Ñorquinco, Ea. Pulmarí, Rucachoroi, Pinalada Redonda and Lago Tromen chronologies had positive factor loadings in the second axis.

In order to identify the causes for the separation of these two sets of chronologies by PC2, the factor loadings of each chronology on the three axes or components were compared with geographic features from each site through a correlation analysis (Table 4). In contrast to non-significant relationships with PC1, PC2 was positively correlated with latitude ($r = 0.52$, $P = 0.03$), longitude ($r = 0.57$, $P = 0.02$) and negatively with elevation ($r = -0.97$, $P < 0.01$). Although most chronologies with positive values on PC2 are located to the south and west on the study region (Fig. 5), the highly significant correlation between the PC2 and elevation suggest that this geographical factor is the variable modulating the PC2 pattern. Chronologies from sites above and under 1,400 m a.s.l. had negative and positive values on PC2, respectively (Table 1). The high association between precipitation and longitude ($r = 0.78$, $P < 0.01$) is in agreement with the west-east rainfall gradient in the study area mentioned above (Table 4).

The correlation analysis shows highly significant positive correlations between residual chronologies (Fig. 6), consistent with the large common interannual variability between records displayed by PC1. The highest correlation coefficients are recorded between chronologies located at similar elevations. Hence, this analysis also indicated that elevation is an important variable modulating sites ordination as shown by PC2. The Nahuel Mapi chronology has the highest mean correlation between chronologies ($r = 0.68$, $P < 0.01$).

In summary, both PC and correlation analyses suggest that there is a strong regional interannual signal in the

Table 4 Correlation matrix between geographic variables and the PCA loadings for the *A. araucana* residual chronologies within the common period 1676–1974 (299 years)

	Lat.	Long.	MAT	AP	Easting	Elev.	North.	PC1	PC2	PC3
Lat.		0.467	0.280	−0.176	−0.076	**−0.536**	0.008	−0.061	**0.523**	0.251
Long.			0.350	**0.775**	0.042	**−0.492**	0.254	−0.200	**0.574**	**0.495**
MAT				0.179	0.174	0.020	0.118	−0.241	−0.055	**0.534**
AP					0.036	−0.234	0.312	−0.255	0.315	0.340
Easting						0.322	−0.166	−0.078	−0.290	0.438
Elev.							−0.178	0.229	**−0.966**	0.029
North.								−0.048	0.162	0.204
PC1									−0.130	0.116
PC2										0.000
PC3										

Lat., latitude; Long., longitude; MAT, Mean annual temperature; AP, Annual precipitation; Easting, sine of the aspect in radians; Elev., elevation (m); North., northing, cosine of the aspect in radians; PC1, PC2 and PC3, factor loadings for the three principal components

Bold numbers indicate significant values at the 0.05 level ($|r| > 0.482$)

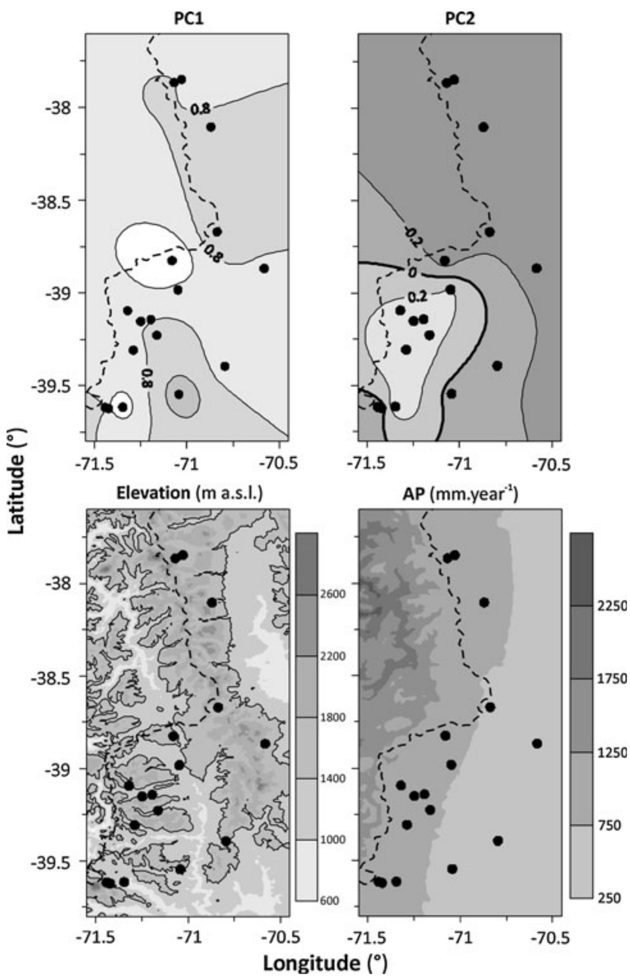

Fig. 5 Maps of regional spatial variation in tree growth determined by the contribution (eigenvalues) of each chronology to PC1 and PC2, elevation and annual precipitation (AP). Isolines of eigenvectors were calculated using the kriging interpolation procedure (Golden Software 2002). Chronology locations and the international boundary are indicated by *circles* and *dashed line*, respectively. In the elevation map, the 1,400-m contour line is indicated by a *solid line*

residual chronologies. So, all series were averaged in a regional composite record and in two subsets, namely a high-elevation group (chronologies above 1,400 m showing negative values in the PC2) and low-elevation group (positive loadings in PC2) (Figs. 5 and 7). Although no differences in the descriptive statistics of the two-group chronologies were observed, the highest rate of growth was recorded in the low-elevation group (Table 5 and Fig. 7). Based on the EPS statistics (Fig. 8), the regional, as well as the high- and low-elevation chronologies can be considered very robust, stable and reliable since 1425, 1445 and 1585, respectively.

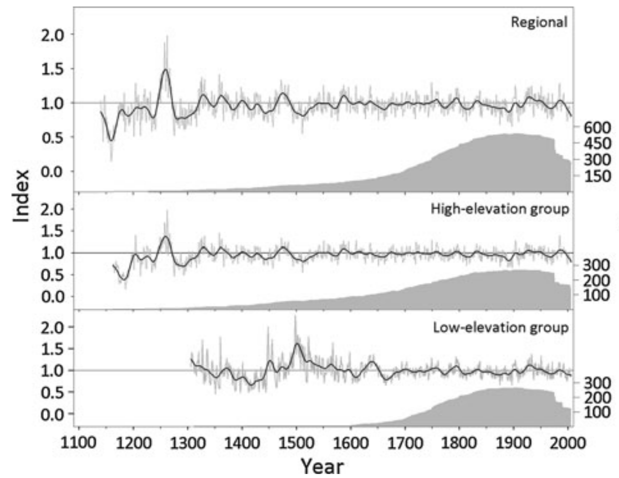

Fig. 7 The regional, high- and low-elevation standard chronologies (*gray curves*). The black lines are superimposed 25-year spline curves. At the bottom, sample sizes are shown as *gray areas*

Climatic influence on *A. araucana* growth

Figure 9 presents the results of correlation between tree growth and seasonal mean temperatures from spring (SON) in the previous year to fall (MAM) during the current growing season. The pattern of response for the regional chronology and the two subsets is very similar. These results show that *A. araucana* growth is negatively correlated with mean seasonal temperatures, particularly during summer (DJF) in the previous growing season. Considering

Fig. 6 Correlation matrix between the *A. araucana* residual chronologies for the common period 1676–1974 (299 years) ordered by elevation. All correlation coefficients are significant at the 0.05 and 0.01 levels ($r = 0.113$ and 0.149, respectively). A correlation-scale index is indicated

	PAR	CAV	CVV	HAC	CHP	PRP	LAN	MAP	PTR	RAH	RUC	REM	LAL	NOR	PIN	PUL
CAV	0.579															
CVV	0.529	0.710														
HAC	0.650	0.726	0.672													
CHP	0.567	0.764	0.753	0.721												
PRP	0.552	0.650	0.632	0.705	0.709											
LAN	0.528	0.675	0.594	0.696	0.637	0.618										
MAP	0.624	0.696	0.635	0.786	0.699	0.722	0.754									
PTR	0.469	0.563	0.542	0.597	0.577	0.632	0.760	0.670								
RAH	0.580	0.618	0.514	0.709	0.576	0.610	0.590	0.741	0.526							
RUC	0.463	0.599	0.626	0.654	0.639	0.561	0.631	0.670	0.569	0.585						
REM	0.496	0.572	0.544	0.619	0.541	0.532	0.649	0.699	0.554	0.536	0.690					
LAL	0.531	0.557	0.503	0.604	0.538	0.583	0.483	0.647	0.443	0.578	0.633	0.652				
NOR	0.420	0.581	0.604	0.611	0.544	0.495	0.575	0.701	0.527	0.542	0.712	0.675	0.615			
PIN	0.451	0.506	0.493	0.561	0.474	0.518	0.589	0.642	0.571	0.533	0.660	0.698	0.620	0.688		
PUL	0.455	0.550	0.508	0.583	0.556	0.505	0.575	0.609	0.489	0.561	0.752	0.663	0.706	0.625	0.683	
TRO	0.385	0.426	0.527	0.510	0.516	0.497	0.547	0.590	0.537	0.463	0.685	0.590	0.547	0.628	0.652	0.599

Scale: < 0.3; 0.3 - 0.4; 0.4 - 0.5; 0.5 - 0.6; 0.6 - 0.7; > 0.7

Table 5 Descriptive statistics for the regional and the high- and low-elevation chronologies

Group	Record period	Raw data		Standard chronology	
		RW (mm)	Mean Sensitivity	Mean RBAR	Autocorrelation[a]
Regional	1140–2006	0.864	0.205	0.130	0.607
High-elevation	1162–2006	0.779	0.202	0.144	0.632
Low-elevation	1306–2006	0.959	0.208	0.139	0.616

RW, Mean ring width, Mean RBAR, mean correlation between series

[a] Autocorrelation, serial correlation coefficient for the chronology at a lag of 1 year (i.e., the first-order autocorrelation)

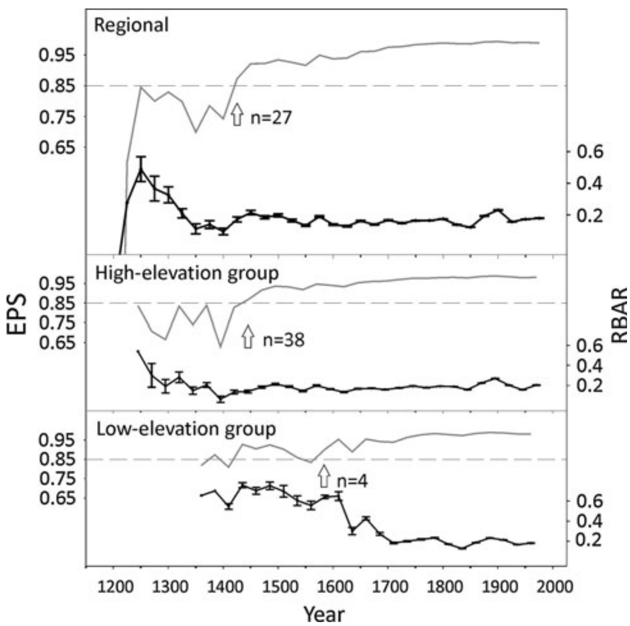

Fig. 8 Running EPS (*gray curves*) and RBAR (*black curves* with ± standard error) for the regional, high- and low-elevation standard chronologies. The *arrows* point at the EPS cutoff date for each chronology before which the chronology was not deemed reliable. The number of samples at these points is also indicated

the two subsets of chronologies, a stronger response to temperature was found in the high-elevation than in the low-elevation group. For precipitation, the quarterly average allowed us to recognize positive relationships between regional growth and rainfall during the current growing season, being significant for spring and fall (SON and MAM, respectively).

Additional evidence for the positive relationships between precipitation and *A. araucana* growth arose from comparing the residual regional as well as the high- and low-elevation chronologies with a precipitation reconstruction from *Austrocedrus chilensis* in northern Patagonia (1600–1988) developed by Villalba et al. (1998). During the interval between 1600 and 1998 (399 years), both records were significantly related ($r = 0.445$, $P < 0.01$; $r = 0.421$, $P < 0.01$ and $r = 0.446$, $P < 0.01$ using the regional, high- and low-elevation chronologies, respectively).

Comparisons between the *A. araucana* regional growth and PDSI showed a positive correlation during the current growing season (Fig. 10). Significant correlations were found between spring and summer PDSI during the current growing season and tree growth for the low-elevation group of chronologies. A negative significant association between Niño 3.4 sea surface temperatures and tree growth at the high-elevation chronologies was recorded for the three quarters of the previous growing season (previous SON: $r = -0.18$, $P = 0.04$; previous DJF: $r = -0.19$, $P = 0.03$; previous MAM: $r = -0.18$; $P = 0.04$). Relationships between *A. araucana* regional growth and the Antarctic Oscillation index (AAO) were negative almost throughout the period analyzed, being only significant during summer (DJF) of the current growing season (Fig. 10).

Spatial correlations between the regional chronology, SST and the geopotential height (850 HPa) were estimated for the area 20°N-85°S/180°E-0°. Consistent with the SST and AAO relationships previously described, the strongest associations between tree growth, tropical sea-surface temperatures and geopotential heights were recorded from January to March during the previous and current growing season, respectively (Fig. 11). Thus, *A. araucana* growth at the regional level is favored by below-average tropical SSTs during the previous growing season and relatively high geopotential heights over Antarctica at the current summer.

Discussion and conclusion

In the context of present and future climate changes, long proxy records are needed to properly document climate variability at different temporal scales. This study provides a regional perspective on the relationship between climate and the radial growth of *A. araucana* across its distribution in Argentina. Despite some difficulties in tree-ring visibility due to the particular *A. araucana* wood anatomy (Schulman 1956), long and statistically reliable chronologies have been developed. All the chronologies show a strong regional common signal. This strong common signal is supported by the high amount of total variance explained by PC1 (62.3%) and the highly significant mean correlation

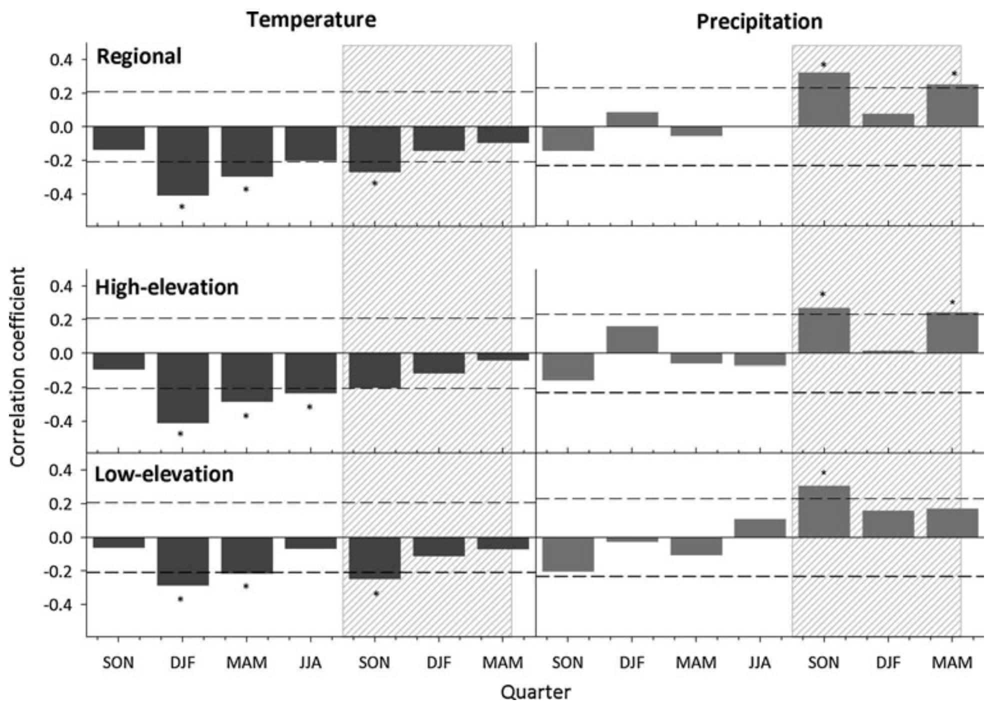

Fig. 9 Correlation coefficients between ring-width indices of the regional, high- and low-elevation residual chronologies with seasonal regional temperature (1916–2005) and precipitation (1929–2001) variations. The *shaded areas* represent the current growing season (October–April) and the *dashed lines* the 95% confidence limits

($r = 0.597$) between all the chronologies over the interval between 1676 and 1974. These observations suggest common climate forcings of tree growth across the region. On this basis we developed a regional chronology covering the interval between A.D. 1140 and 2006 (866 years long) and including 621 *A. araucana* tree-ring series from its entire distribution in Argentina. The greater replication in this chronology provides a solid record with better statistics (indicated by RBAR and EPS) than the individual chronologies.

Based on the PC2 contributions, two groups of chronologies were clearly distinguished: a high- and a low-elevation group. Although relatively small changes in elevation do not affect tree growth by itself, it is a site factor influencing mean annual precipitation and temperature that do have physiological effects on tree growth (Fritts 1976). Many studies have demonstrated the indirect effect of changes in altitude on tree growth in many regions of the world (Fritts et al. 1965; Norton 1985; Buckley et al. 1997; Splechtna et al. 2000; Wang et al. 2005; Leal et al. 2007) as well as in the southern Andean forests (Villalba et al. 1997; Schmelter 2000; Massaccesi et al. 2008).

Based on monthly comparisons between tree growth and climate, Villalba (1995) reported that the growth of *A. araucana* was negatively related to temperatures during January, February and March during the previous summer. The present study confirms this relationship on a regional scale based on the analysis of quarterly (seasonal) temperatures. In addition, our results show a clear response of *A. araucana* to precipitation consistent with sampling on some precipitation-sensitive sites. A positive association with precipitation during spring and summer of the current growing season provides support to the sensitivity of *A. araucana* to water availability. This fact was clearly confirmed by the positive and significant correlation with a reconstruction of nearly 400 years of November–December rainfall for northern Patagonia developed from *A. chilensis* ring-width chronologies (Villalba et al. 1998).

Because the PDSI includes information on precipitation, temperature, evapotranspiration and soil moisture, it is considered a better indicator of drought conditions than precipitation alone (Cook and Jacoby Jr 1977; Stahle and Cleaveland 1988; Meko et al. 1993; Cook et al. 1999). The growth of *A. araucana* shows a positive relationship with PDSI in the growing season (i.e. better growth in wetter years); however, this relationship is not as strong as that reported for the xeric *A. chilensis* (Christie et al. 2010; Mundo et al. 2010). Meteorological records are scarce along the *A. araucana* distribution in Argentina and Chile, and the apparent lower sensitivity of this species to precipitation might reflect this important limitation. Future analyses based on individual meteorology stations within the range of *A. araucana* may yield more consistent results. However, the lack of reliable meteorological records and soil profile data, variables necessary for the calculation of the PDSI, makes this task quite difficult now.

Significant correlations between *A. araucana* growth, sea surface temperature in the Niño 3.4 region (an indicator of the ENSO activity) and the AAO are consistent with the observed relationship between local climate anomalies and

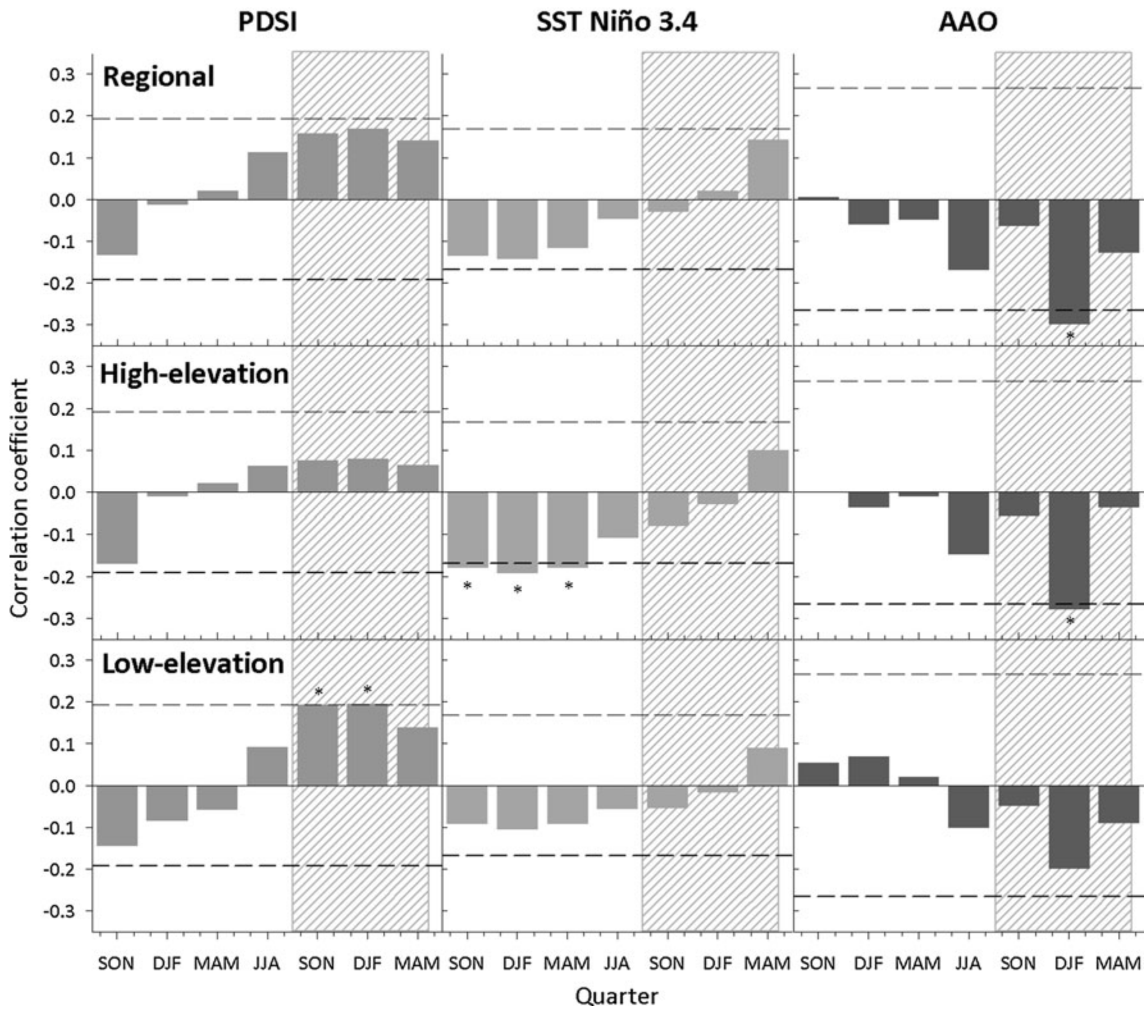

Fig. 10 Correlation coefficients between ring widths of the residual regional, the high- and low-elevation residual chronologies and quarterly PDSI (1902–2005; Dai et al. 2004), sea surface temperature for Niño 3.4 region (SST Niño 3.4: 1871–2006) and the Antarctic Oscillation index (AAO: 1948–2002). The *shaded areas* represent the current growing season (October–April) and the dashed lines the 95% confidence limits

these indices. The correlation with the seasonal SST Niño 3.4 (SON, DJF, MAM of the previous growing season) reflects the occurrence of above-average summer temperatures in northern Patagonia during positive SST anomalies in the Niño 3.4 region. Based on instrumental records, Garreaud et al. (2009) documented a positive and significant association between the multivariate ENSO index (MEI) and summer temperature in northern Patagonia.

The negative relationship of *A. araucana* growth with AAO reflects the regional rainfall anomalies induced by the AAO. During the positive phase of the AAO, the Westerlies shift southwards, precipitation is reduced in northern Patagonia and a persistent water deficit affects the *A. araucana* growth. Aravena and Luckman (2009) reported significant negative rainfall anomalies in northern Patagonia concurrent with positive AAO indices. Thus, the positive relationship between above-average sea level pressure over the sub-Antarctic domain and the growth of *A. araucana*, shown in Fig. 11, is consistent with positive geopotential heights around Antarctica during the negative phase of the AAO. In summary, the reduced radial growth of *A. araucana* is associated with high temperatures in the previous and current summers and/or low precipitation during the current growing season. These climatic anomalies are largely modulated by above-average SST Niño 3.4 in the previous spring, summer and fall and the positive phase of the AAO during the summer of the current growing season (Fig. 10).

The increase of water availability with elevation introduces small differences in the growth responses of *A. araucana* to climate. A negative significant correlation was recorded between spring temperature and ring width at low elevation. Consistently, the low-elevation chronologies have stronger positive correlations with precipitation

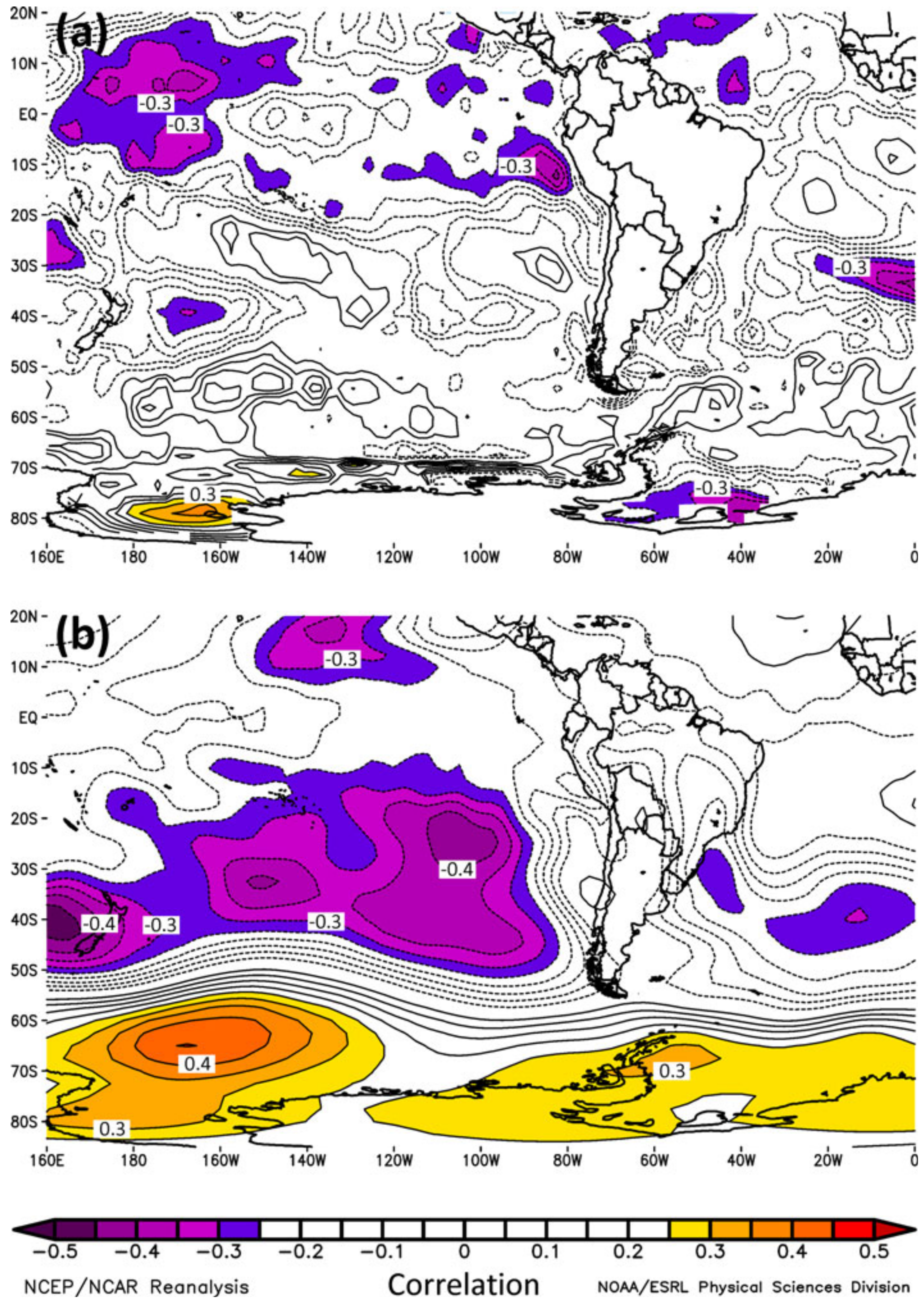

Fig. 11 Spatial correlation patterns during the interval 1948–2006 between the residual regional chronology and SST during the previous JFM (**a**), and 850 HPa geopotential height during the current JFM (**b**). Correlation values are shown at the *bottom*. *Solid* and *dashed* contours indicate positive and negative correlations, respectively. Only significant patterns are shown in *color*. Data for the SST and geopotential height at 850 hPa for the period 1948–2006 were obtained from the National Oceanic and Atmopheric Administration website (http://www.esrl.noaa.gov/psd/data/correlation/)

during spring and the PDSI during spring and summer in the current growing season. These observations clearly imply that *A. araucana* tree growth at low altitudes is controlled by spring-summer moisture availability in the current growing season. Many studies near the lower forest border in Mediterranean and semi-arid regions showed that tree growth is influenced by precipitation (Richter and Eckstein 1990; Till and Guiot 1990; Stahle and Cleaveland 1992; Hughes et al. 1994). On the contrary, water deficit rarely limits the alpine or high-elevation forest growth (Tranquillini 1979; Villalba et al. 1997; Rigling et al. 2002; Wilson et al. 2005). In the southern Andes, Lara et al. (2001, 2005) found that precipitation is the limiting factor controlling the radial growth of the subalpine *Nothofagus pumilio* at the northern sites of its distribution. The extended dry summer due to the Mediterranean-type climate prevailing at these sites may explain the relationship between *N. pumilio* radial growth and precipitation at the treeline.

Current climate changes show a more or less constant increase in temperatures and a long-term decrease in rainfall during recent decades in the northern Patagonian Andes (Fig. 12). Therefore, it is not surprising that growth has declined in all three regional chronologies since the late 1970s. Simulation models for future climates released

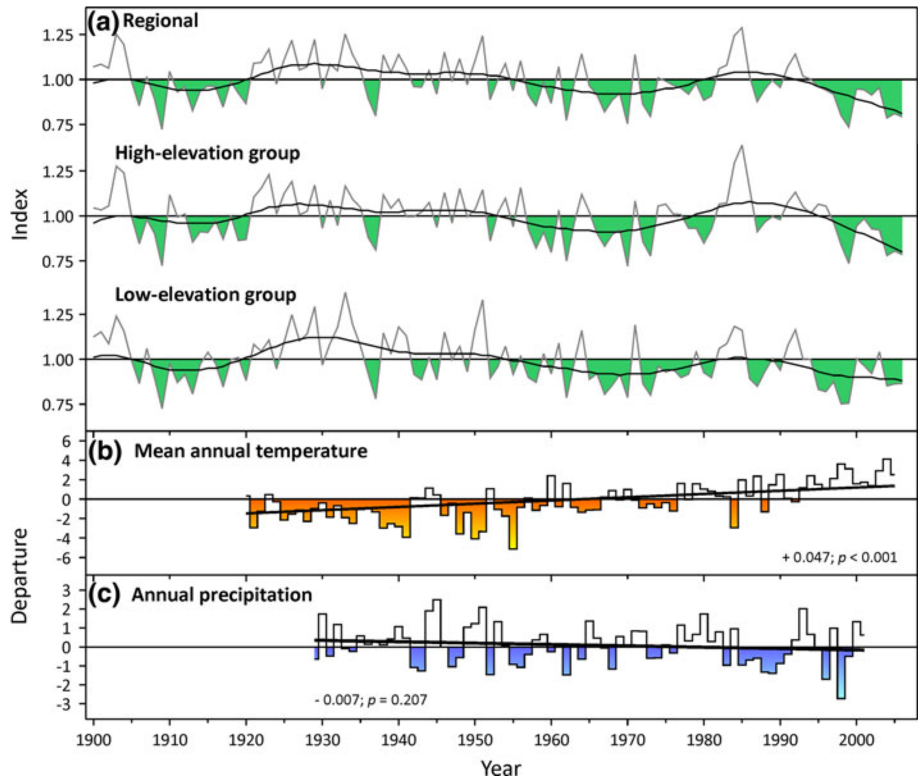

Fig. 12 Comparison between interannual variations in the regional, high- and low-elevation residual chronologies (**a**) and departures in regional temperature (**b**) and precipitation (**c**) since 1900. In panels **b** and **c**, the linear trends for temperature and precipitation are indicated. Slope and significance of both linear trends are also indicated

by the IPCC in its Fourth Assessment Report (Christensen et al. 2007) predict even drier conditions over the southern Andes for the twenty-first century. Continental simulations carried out by Labraga (1998) predict a decrease in summer rainfall of 2–42% by 2070 in northwestern Patagonia. Based on these simulations, a further decline in the rate of growth of *A. araucana* would be expected in the coming years. This should be taken in consideration for the implementation of the conservation and management strategies of the *A. araucana* forests in the near future.

Based on its statistical properties, temporal extent and geographical distribution, these tree-ring chronologies of *A. araucana* represent a valuable network of proxy records to develop dendroclimatological and dendroecological studies in the region. Considering the statistics that measure the common signal in the chronologies (RBAR and EPS), temperature and precipitation reconstructions longer than 600 years could be developed from the records presented in this study. Based on *A. araucana* sensitivity to water deficit, a PDSI reconstruction similar to that recently published by Christie et al. (2010) with *A. chilensis* tree-ring chronologies might be developed. In addition, the present network of chronologies can be used to complement the preliminary streamflow reconstructions of the Limay and Neuquén Rivers flow developed by Holmes et al. (1979) using seven tree-ring chronologies (five from *A. araucana* and two from *A. chilensis*). The extensive and well replicated tree-ring network currently available, along with substantial improvements in chronology and reconstruction developments, provides new opportunities to develop more consistent and longer hydroclimatic reconstructions for this important region of the southern Andes.

Acknowledgments This research was supported by the Inter-American Institute for Global Change Research (IAI-CRN 2005 and 2047) and by a CONICET doctoral fellowship (National Council for Scientific and Technical Research of Argentina). We are grateful to Eduardo Barrio, Alberto Ripalta, Lidio López, María Alejandra Giantomasi, Sergio Piraino, Ana Srur, Carolina Szymañsky and Andrés Manceñido for research assistance. We thank the Administración de Parques Nacionales, Áreas Naturales Protegidas del Neuquén, Corporación Interestadual Pulmarí, and the owners and administrators of Ea. Nahuel Mapi and Rahue site for facilitating this research. We are greatly indebted to Brian Luckman for comments and corrections on an early version of this manuscript. We also thank the communicating editor and two anonymous reviewers for helping to improve the final version of this manuscript.

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