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Weakening climatic signal since mid-20th century in European larch tree-ring chronologies at different altitudes from the Adamello-Presanella Massif (Italian Alps)

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ABSTRACT

Tree rings from temperature-limited environments are highly sensitive climate proxies, widely used to reconstruct past climate parameters for periods prior to the availability of instrumental data and to analyse the effect of recent global warming on tree growth. An analysis of the climatic signal in five high-elevation tree-ring width chronologies of European larch (*Larix decidua* Mill.) from the tops of five different glacial valleys in the Italian Central Alps revealed that they contain a strong summer-temperature signal and that tree-ring growth is especially influenced by June temperatures. However, a moving correlation function analysis revealed a recent loss of the June temperature signal in the tree-ring chronologies. This signal reduction primarily involves the two lowest-altitude chronologies. It is probable that the observed increasing importance of late-summer temperature for tree-ring growth over the past 50 yr is an effect of the lengthening growing season and of the variations in the climate/tree-ring relationship over time. All the chronologies considered, especially those at the highest altitudes, show an increasing negative influence of June precipitation on tree-ring growth. The climatic signal recorded in tree-ring chronologies from the Italian Central Alps varies over time and is also differentially influenced by climatic parameters according to site elevation.

Introduction

Tree-ring chronologies from temperature-limited environments are widely used for annual-scale reconstructions of past summer temperatures at both regional and global scales (e.g., Briffa et al., 1988a,b, 1992; Mann et al., 1998, 1999; Wilson and Luckman, 2002, 2003). In addition to total ring width, several other tree-ring proxies have been used to infer past climatic information, including analyses of latewood maximum density (e.g., Briffa et al., 2004) and, more recently, stable isotopes (e.g., Treydte et al., 2007). Several studies have detected a recent loss of climate sensitivity in ring-width chronologies at high-latitude sites (Briffa et al., 1998a,b; Vaganov et al., 1999; Barber et al., 2000; Jacoby et al., 2000; Esper et al., 2003). A similar weakening of the correlation between climate and tree growth over the latest few decades has also been found for several conifer species at the upper treeline in the European Alps (Carrer et al., 1998; Büntgen et al., 2006; Carrer and Urbinati, 2006; Leonelli et al., 2009). However, this change in sensitivity does not seem to be ubiquitous across the Alps, and several authors have used high-elevation conifer chronologies to develop summer temperature reconstructions that exhibit no sensitivity decrease in the recent period (Wilson and Topham, 2004; Frank and Esper, 2005a,b; Büntgen et al., 2008).

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Carrer and Urbinati (2006) explored the dendroclimatic potential of European larch (*Larix decidua* Mill.) for use as a climate proxy. Their analysis was based on a data set of 17 chronologies taken from sites distributed widely across the Eastern Italian Alps from 10.55° E to 13.69° E (Fig. 1). In this study, we performed a dendroclimatic analysis on trees of this species at a finer spatial scale in the Adamello-Presanella Massif (APM) in the Italian Central Alps. The APM constitutes a well-defined unit within the Italian Central Alps. It is separated from the surrounding mountain ranges by broad and deep valleys and hosts one of the largest glacial systems of the entire Alpine Arch (Baroni and Carton 1987, 1996; Baroni et al., 2004). We developed tree-ring chronologies from five sites in the APM spanning an altitudinal gradient of more than 300 m, allowing us to explore the suitability of larch forests in different environmental settings for dendroclimatic reconstructions.

Study area

The APM lies in the central-southern sector of the central Italian Alps (Rhetian Alps, 45° 54′–46° 19′ N; 10° 21′–10° 53′ E), covers an area of more than 1100 km^2, and hosts peaks exceeding 3500 m in elevation. The major peaks of the group are Cima Presanella (3568 m), Mount Adamello (3539 m), and Mount Carè Alto (3463 m) (Fig. 1). The APM presently hosts approximately 100 glaciers, primarily in the northern and central sectors of the Group. The Adamello Glacier, the widest and most impressive glacier in the entire Italian Alps,

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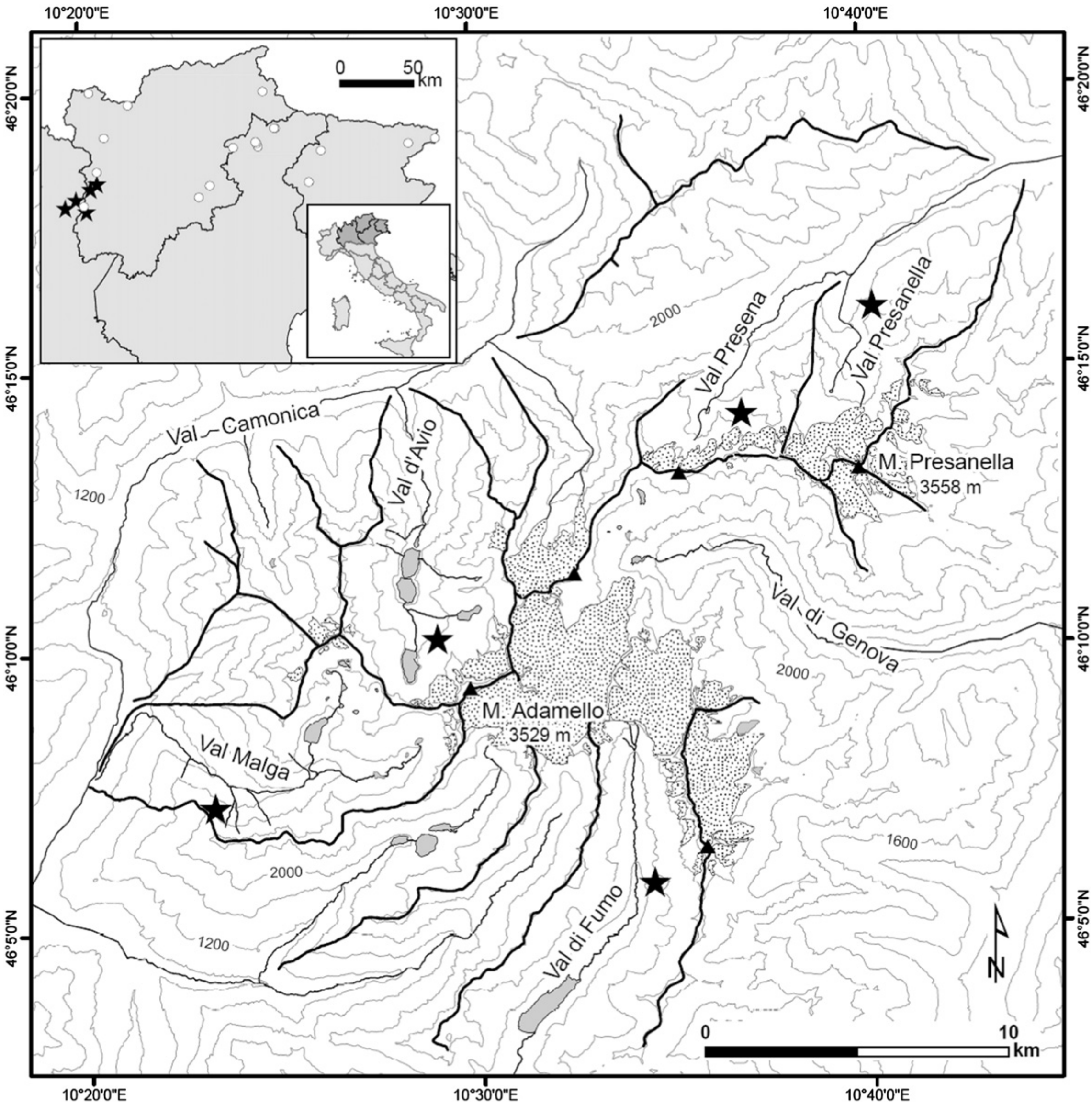

Figure 1. Sketch map of the study area. Stars indicate the sampling-site locations. Dashed areas indicate the glacial bodies. The white dots in the box indicate the locations of the 17 sites of Carrer and Urbinati (2006).

occupies the summit area of the massif (Baroni and Carton 1990, 1996; Baroni et al., 2004; Ranzi et al., 2010).

The five sampling sites selected for this study are located at the heads of five different glacial valleys surrounding the APM (Fig. 1). All the sampling sites are included in the territories of two adjacent Natural Parks, the Adamello-Brenta Natural Park and the Adamello Regional Park. At all five sampling sites, open *Larix decidua* Mill.–*Picea abies* L. stands dominate the forest cover above 1800 m a.s.l. At higher altitudes, at approximately 2000 m a.s.l., spruces are typically replaced by an open mixed association of larch and stone pine (*Pinus cembra* L.) with a generally species-poor undergrowth.

Materials and methods

Tree-ring data

Five ring-width chronologies were developed from living European larch trees (*L. decidua* Mill.) at five sampling sites located in the open forest near the treeline. The mean altitudes of these sites ranged from 1850 m a.s.l. (MAL) to 2160 m a.s.l. (PRS) (Table 1).

To minimise the possible effects of stand competition, only dominant, open-grown trees with undisturbed canopies were sampled. Trees showing external evidence of non-climatic growth disturbances, such as lightning scars and broken branches or crowns were excluded.

In the upper part of the Val Malga (MAL) site gravitative mass movements, primarily debris flows, rock falls, and rock avalanches disturbed the underlying vegetation, and thus potentially altered the climatic signal recorded by the trees (e.g., Pelfini et al., 2006).

Table 1
Main geographical characteristics and codes of the five study sites for European larch. Sites are ordered according to a decreasing altitude.

Site code	Site name	Mean altitude (m)	Latitude N	Longitude E	Site aspect
PRS	Val Presena	2160	46° 23′	10° 60′	NNE
AVI	Val d'Avio	2150	46° 10′	10° 28′	NNW
FUM	Val di Fumo	1990	46° 05′	10° 34′	WNW
PRL	Val Presanella	1910	46° 25′	10° 65′	NNE
MAL	Val Malga	1850	46° 07′	10° 25′	WNW

For this reason the sampled trees were chosen at a lower altitude than in the other four sites (MAL mean site altitude 1850 m).

At least two cores from opposite sides were extracted from the tree stems according to standard dendrochronological sampling procedures (Stokes and Smiley, 1968). All cores were obtained with an increment borer at breast height (~1.30 m from ground level), coring horizontally and at 90° with respect to the slope direction to avoid the possible presence of compression wood. In the laboratory, each core was dried and mounted on wooden supports. A transverse surface of the cores was cut with a sharp cutter blade and sanded with progressively finer sandpaper to make the tree rings clearly visible (Ferguson, 1970; Pilcher, 1990). Tree-ring widths were measured with a precision of 0.01 mm using a LINTAB increment measuring table (RinnTech) in conjunction with TSAPwin software (version 0.53; Rinn, 2005). Broken cores or cores with evident signs of mechanical disturbance were discarded. The ring-width series were cross-dated visually and statistically (Fritts, 1976) with TSAPwin.

Only ring-width series longer than 100 yr were used in the successive analyses, and only ring-width series with high year-to-year agreement between interval trends (Gleichläufigkeit index, Glk > 0.60; Schweingruber, 1988) and t-values (t) > 2.5 were retained for computing the mean site chronologies. The correct cross-dating was further verified using the International Tree-Ring Data Bank COFECHA software (Holmes, 1983; Grissino-Mayer, 2001), which identifies segments within each ring-width series that may contain erroneous cross-dating or measurement errors.

The ring-width series were standardised and the mean site residual chronologies calculated using the ARSTANwin programme (Cook and Holmes, 1984; Cook, 1985). A double detrending method was used to improve the climate signal contained in the ring-width series, reducing the noise caused by systematic non-climatic change due to tree age and potential endogenous disturbance events (Cook and Briffa, 1990). First, a negative exponential curve or a linear regression line was fitted to the ring series. Each value of the time series was then divided by the value predicted by a cubic smoothing spline function. The wavelength of the spline was fixed at 67% of the mean length of the series, with a 50% frequency cut-off (Cook and Briffa, 1990). The autocorrelation was removed from each series using an autoregressive model (Cook and Briffa, 1990). Individual indexed series were then included in the mean site residual chronology with a bi-weight robust estimate of the mean (Cook, 1985). Several statistics were used to evaluate the five residual chronologies: the mean sensitivity and standard deviation to assess high-frequency variations (Fritts, 1976) and the mean interseries correlation and first order autocorrelation to identify possible persistence retained after standardisation. To assess the adequacy of replication in the early years of the five chronologies, we used the Subsample Signal Strength (SSS) (Wigley et al., 1984). We limited our analysis to the period with SSS > 0.85 (Wigley et al., 1984).

The five chronologies were statistically compared over their common period (1818–2004) using the Pearson's correlation coefficient (r). Moreover, a hierarchical cluster analysis was performed according to the average linkage method, using the Euclidean distance as a measure of similarity.

Climate data

Gridded monthly and seasonal mean temperature and precipitation records were obtained from the HISTALP data set (Auer et al., 2007, http://www.zamg.ac.at/histalp) with the reference grid point 10° N 46° E. In the HISTALP data set, temperature and precipitation anomalies are referred to the 20th century mean (1901–2000) and were derived only for homogenised data, both for the monthly temperature series (2004–11 release) and the monthly precipitation series (2004–2008 release) (Auer et al., 2007). The temperature data span the years from 1760 to 2007 (247 yr), and the precipitation data span the years from 1799 to 2003 (204 yr).

Analysis of climate–growth response

Climate/tree-ring growth relationships were tested with standard Correlation Function Analysis (CF) and Response Function (RF) Analysis (Fritts, 1976). Moreover, a Moving Correlation Function (MCF) analysis was used to verify the stability of the climate–growth response over time. These analyses were performed using the software package DENDROCLIM2002 (Biondi, 1997; Biondi and Waikul, 2004). Each bootstrap estimate was obtained by generating 1000 samples and running the same numerical computation on each sample. For each interval, the median coefficients estimated from the 1000 bootstrap samples are reported in the output and are plotted only if they are significantly different from 0 at the 0.05 probability level.

A monthly climate analysis was performed for both the mean monthly temperatures and the total monthly precipitation. A total of 15 climate variables were chosen from July of the year before growth ($t-1$) to September of the year of growth (t). For the seasonal analysis, we chose four mean temperature variables and four total precipitation variables. These variables ranged from the summer of the previous year (JJA − 1) to the summer of the current year of growth (JJA). The analysis was performed over the period 1818–2004 with the temperature data and over the period 1818–2003 with the precipitation data. The length of the calibration period (60 yr), twice the standard time length normally used in climatological studies, has previously been used in similar dendroclimatologic studies on the Ortles-Cevedale Group (Leonelli et al., 2009, 2011). We performed this analysis with all five residual chronologies and with a composite chronology (ALL). The ALL chronology was obtained by averaging all of the residual chronologies except for the MAL chronology. The MAL chronology was omitted from the composite because this chronology always showed lower correlation values with climatic factors than those shown by the other four chronologies (Table 3).

To highlight the differences between the early and late parts of the period covered by the MCF analysis, a t-test of differences (confidence level 0.95, α level 0.05) was performed on the correlation coefficient (CC) values computed with the ALL chronology. The full time series was divided into two parts of 63 and 64 yr (1878–1940 and 1941–2004, respectively). The mean values, the variability, and the distributions of the CC values were evaluated for the two time periods. A trend analysis (linear trend model) was performed on the CC values relative to the most important climatic parameters (June mean temperatures) involved in tree growth for each chronology over the past 54 yr (1950–2004).

To investigate the response of European larch to extreme warmth, we analyzed the responses of the five tree-ring width chronologies to the heat wave that occurred in Europe, including the Alps, during summer 2003. This analysis was performed by directly comparing the ring-width indices with the temperature anomalies (Pilchler and Oberhuber, 2007; Leonelli et al., 2009).

Results

Descriptive statistics of the chronologies

The comparison of the five tree-ring chronologies reveals similarities and differences among the study sites. The correlation coefficient values (r) computed between the chronologies are noticeably high (0.66–0.75) for four of the five chronologies (PRL, FUM, AVI, PRS) (Table 2). The MAL chronology shows correlation values that are low compared to those obtained from the other four mean site chronologies, as indicated by the computed r values and by the cluster analysis of similarities performed on the data from the period covered by all five chronologies (1818–2004) (Table 2, Fig. 2).

Table 2
Pearson correlation coefficients (r) between the five mean residual chronologies over their common period (1818–2004); α level = 0.05.

	MAL	FUM	PRS	PRL
FUM	0.54			
PRS	0.42	0.71		
PRL	0.52	0.75	0.66	
AVI	0.42	0.72	0.68	0.67

The AVI chronology spans 459 yr and is the longest chronology of the entire data set. It includes the individual time series with the highest mean length (348 yr) and the highest mean series intercorrelation (0.68). The mean sensitivity (MS) values are >0.2 for all of the five chronologies and range between 0.23 (PRL) and 0.29 (FUM) (Table 3). The lowest MS values were observed for the PRL and MAL residual chronologies, the two chronologies with the lowest mean site altitudes. The five residual chronologies were truncated at the first year with subsample signal strength (SSS) > 0.85 (Fig. 3).

Climate–growth response

The monthly and seasonal CF analyses performed over the entire time period (1818–2004) show a strong summer (JJA) mean temperature signal in the chronologies, with the June mean temperatures presenting the highest CC values (Fig. 4). Overall, the highest correlation values were obtained for the June mean temperatures, with the AVI and PRS chronologies showing a predominant influence of early summer (June) mean temperatures on tree growth.

The analysis also reveals a positive influence of the mean temperatures in the autumn of the previous year (SON − 1) on tree-ring growth. The highest CC values were obtained for the September−1 and October−1 mean temperatures, but we also found that all five chronologies are positively correlated with the November−1 and December−1 temperatures. The RF analysis performed with monthly and seasonal temperature variables shows similar results (Fig. 4).

The correlation values of the JJA and June mean temperatures show a direct relationship with the mean site elevation (Fig. 5), with the chronologies from the highest altitudes (PRS and AVI) showing the strongest climatic signal.

The analysis of precipitation shows significant negative correlation values for all the five chronologies with the June precipitation (up to $r = -0.29$ for the AVI chronology) (Fig. 6). Significant positive correlation coefficients were found between December−1 precipitation and the PRS and PRL residual chronologies and between March precipitation and the FUM chronology (Fig. 6). The RF analysis

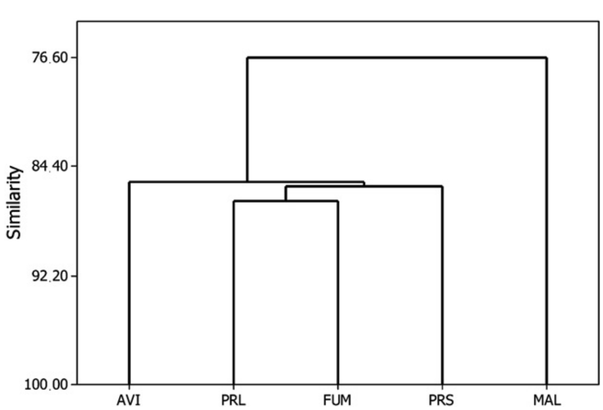

Figure 2. Dendrogram resulting from the hierarchical cluster analysis, average linkage method, Euclidean distance as a measure of similarity.

Table 3
Essential statistics of the five European larch residual chronologies.

Statistics	MAL	PRL	FUM	AVI	PRS
First year of chronology	1807	1550	1710	1550	1645
Last year of chronology	2008	2005	2008	2007	2004
Chronology length (year)	202	456	299	459	360
Number of trees	11	14	13	11	8
Number of radii	22	30	26	22	16
Mean length of series	152	257	215	348	179
Mean ring width (mm)	1.87	1.16	1.27	0.78	0.99
Series intercorrelation	0.66	0.63	0.66	0.68	0.64
First year SSS > 0.85 (min. number of sample)	1816 (4)	1596 (3)	1738 (3)	1589 (3)	1818 (3)
Mean sensitivity	0.26	0.23	0.29	0.26	0.28
Standard deviation	0.21	0.20	0.24	0.22	0.25
Variance in 1st principal component (%)	59.4	48.5	59.5	61.3	57.7
First order autocorrelation	−0.108	−0.009	−0.002	−0.023	−0.061

shows significant negative correlation values for all the five chronologies with June and JJA precipitation (Fig. 6).

The moving correlation function (MCF) analysis confirms the predominant influence of early summer mean temperatures on tree growth but shows that the climate/growth relationship has varied markedly over time. The five larch chronologies show a non-stationary climate response, particularly for the May and June mean temperatures. The MCF analysis performed with the May mean temperatures shows a long-term increasing trend in the CC values (Fig. 7a). This trend is most evident for the period 1900–1960. A slight decrease started in the 1960s and was followed by a renewed increase in the CC values for the latest years of the analysis. The increasing positive correlation between ring widths and May mean temperatures is more evident for the MAL and PRL chronologies (mean site altitude < 1900 m a.s.l.) in recent decades. The difference between the first and the second periods of comparison is significant ($p < 0.001$). The MCF analysis performed with the June mean temperatures (Fig. 7b) shows that the CC values have a synchronous decreasing trend that begins in the 1960s. Although a t-test of the differences between the two time periods of comparison shows a generally stable signal ($p = 0.95$) and a regression line computed for the CC values of the ALL chronology reveals a highly stable signal, the last decades of the chronology show a reduction in the strength of the relationship between tree growth and June mean temperatures. Especially for May, a slight increase in the CC values is visible in the latest years (beginning in approximately 2000) of the time series. In the MCF analysis performed with the May and June mean temperatures, the MAL residual chronology, which has the lowest mean site altitude (1850 m a.s.l.), differs from the trend shown by the other four chronologies. The MAL residual chronology has the highest correlation with the May mean temperatures and the lowest with the June mean temperatures, and it shows similar values for the two periods of comparison. The PRL chronology, which has the second-lowest mean site altitude value (1910 m a.s.l), shows the most evident decreasing trend in the CC values computed with the June mean temperatures.

The MCF computed with the July mean temperatures (Fig. 7c) reveals a slight increasing trend in the CC values for the three chronologies representing high-altitude sites (> 1900 m a.s.l.), with significant differences between the earliest and latest periods ($p < 0.001$). The MAL and PRL chronologies show the lowest CC values computed with the July mean temperatures, but the climate/tree-growth response is also quite stable for these chronologies.

Most of the correlations computed over the entire period of analysis with the August mean temperatures (Fig. 7d) are not significant. Positive significant values are found only for the PRL and PRS chronologies. In the MCF analysis, a tendency towards a synchronous

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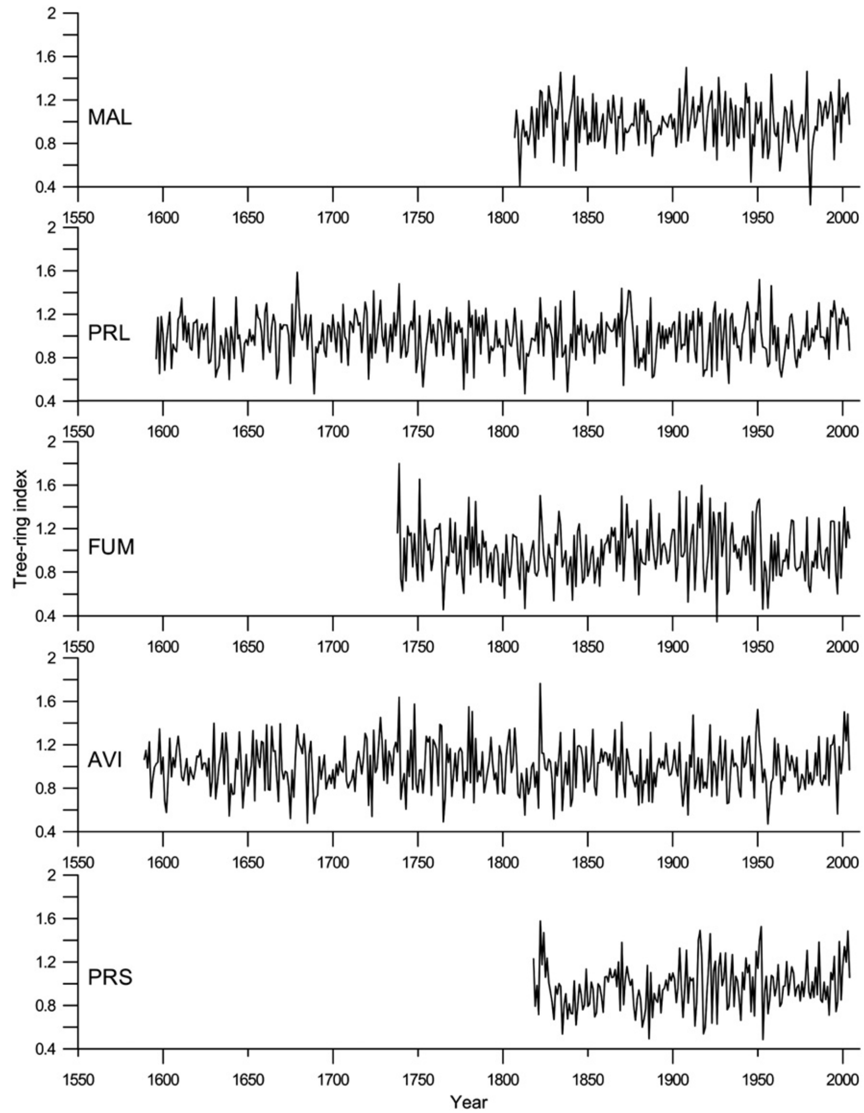

Figure 3. The five residual chronologies of *Larix decidua* Mill. ordered according to the mean site altitude. Chronologies are reduced to the time period with SSS > 0.85.

increment in the CC values starting from approximately 1960 is clearly visible. In the earliest part of the analysis, the CC values are consistently negative or slightly above zero, and their distributions vary relatively little around the mean. In the more recent portion of the chronologies, the CC values are more widely distributed and extend from the minimum to the maximum values of the series. The significant differences between the two compared periods are clearly highlighted in the ALL chronology by a low p-value (<0.001).

The MCF analysis conducted with the JJA mean temperatures shows that the MAL and PRL chronologies have the weakest response to the summer mean temperatures and that this response is generally stable. In contrast, the three chronologies with mean site altitude > 1900 m a.s.l. reveal higher CC values and a trend of generally increasing correlations (Fig. 7f).

The decreasing trend in the correlation values for the recent period is particularly pronounced in the case of the June mean temperatures, the climatic parameter principally involved in larch growth at our sites. The trend analysis conducted on the June moving CC values over the recent time period (1950–2004) shows negative angular coefficient values for the five trend models (Fig. 8). The PRL chronology shows the steepest decreasing trend for the recent period and the lowest value of the angular coefficient.

The correlation values computed between the tree-ring indexes and the JJA mean temperatures show that the five mean site chronologies did not respond linearly to exceptionally high temperatures. This finding is apparent from the 2003 ring width-index values, which do not differ noticeably from the mean. However, the two chronologies from the highest-altitude sites (PRS and AVI) show wider 2003 ring-width values (Fig. 9).

The MCF analysis of long-term changes in the total monthly precipitation/tree-ring growth relationship shows, as is the case for temperature, that the climate/tree-ring growth response was not stable over the entire period of analysis (1818–2003). We found significant correlation coefficient values only for the mean precipitation of December−1 (Fig. 10a) and of June of the current year (Fig. 10b). In both cases, all five residual chronologies show a synchronous and generally non-stationary trend in the CC values. The CC values computed with December−1 precipitation become non-significant in recent decades, whereas the CC values computed with June precipitation are negative overall and vary from non-significant to significant values in the recent period. For June precipitation, we found a divergence between the earliest and recent parts of the analysis (p<0.001), with the PRS chronology (at the highest altitude, 2160 m a.s.l.) showing the most pronounced

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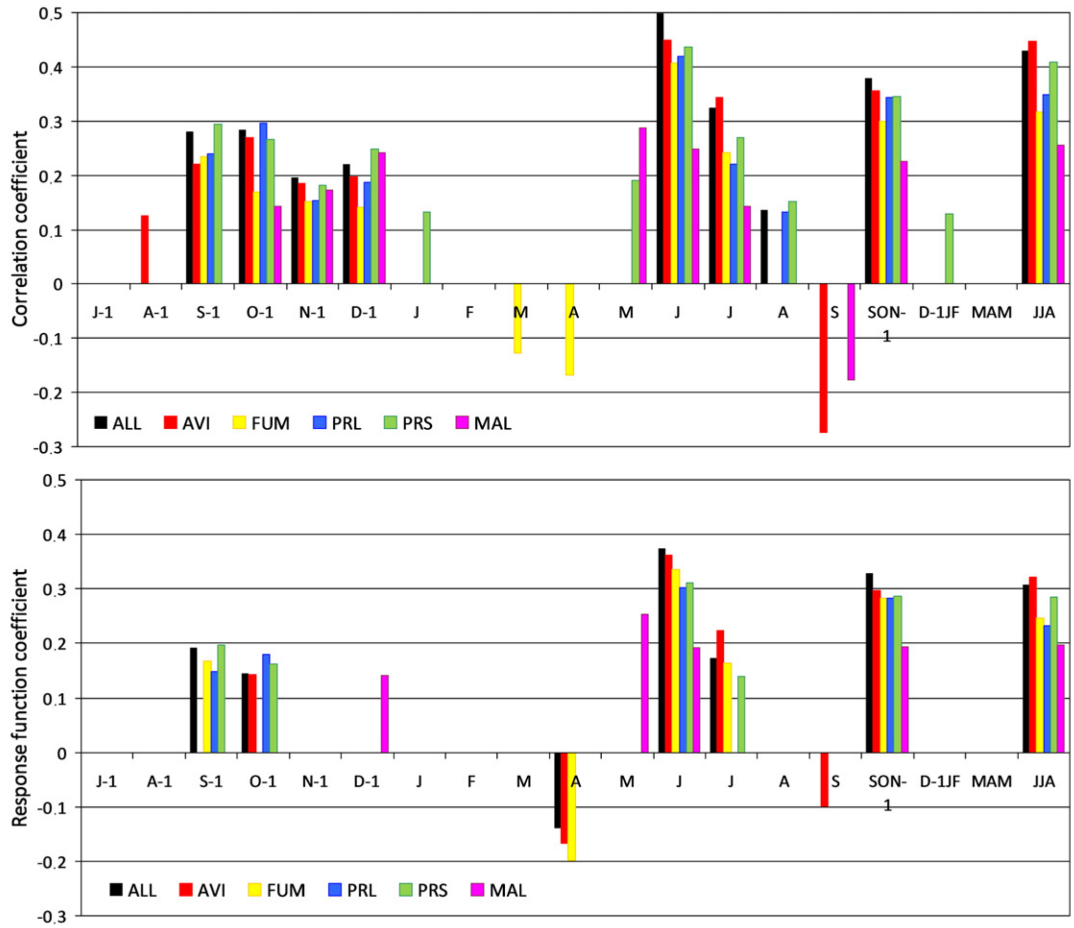

Figure 4. Correlation function (top) and response function results (bottom), coefficients are computed over the time period 1878–2003 between the five residual chronologies plus the ALL chronology and the monthly and seasonal temperature variables. Only statistically significant correlation values are showed (significance test: 95% percentile range, $p<0.05$).

decreasing trend. The CC values range from approximately −0.23 (at the lowest altitudes, PRL chronology, 1910 m a.s.l.; MAL excluded) to approximately −0.54 (PRS chronology) in the last decades of the analysis. Overall, the CC values calculated for the June precipitation show the same type of trend observed for the June mean temperature, but in an inverse direction.

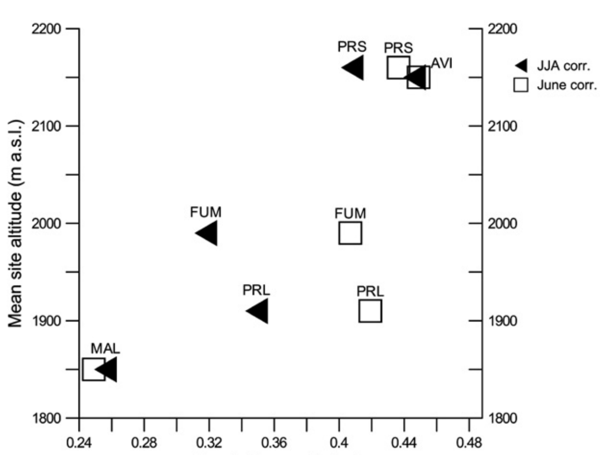

Figure 5. Relationship between mean site altitude and JJA and June correlation coefficients.

Discussion

This study, focused on larch stands on a single alpine massif, shows that temperature, rather than precipitation, exerts the primary control on the radial growth of larch at the upper treeline. This finding confirms the results of previous studies conducted on broader scales (Jacoby and D'Arrigo, 1989; Briffa et al., 2002; Esper et al., 2002a,b, 2003; Carrer and Urbinati, 2006). We have also found that the influence of temperature on tree-ring growth is partially dependent on the mean site altitude, as revealed by the observation of a stronger climatic signal at the highest altitudes (Fig. 5).

The response of larch to climate is driven primarily by the June mean temperature. However, at a smaller scale in a study area limited to a singular alpine massif, the results of our study confirm the temporal instability in climate/growth relationship reported by Carrer and Urbinati (2006) for a *L. decidua* chronology data set in the Eastern Italian Alps and by Leonelli et al. (2009) for a high-altitude *P. cembra* tree-ring network in the Ortles-Cevedale area (Central Italian Alps).

The MCF analysis revealed that climate parameters primarily involved in larch growth at the treeline (June temperature and precipitation) have significant unstable responses and substantial variability over time. Leonelli et al. (2009) obtained similar decreasing trends with June mean temperatures and increasing negative trends with June mean precipitation for the last few decades, albeit with a different conifer species. The similarity of our results to these results previously obtained for a stone pine dendroclimatic network developed in an adjacent mountain region could

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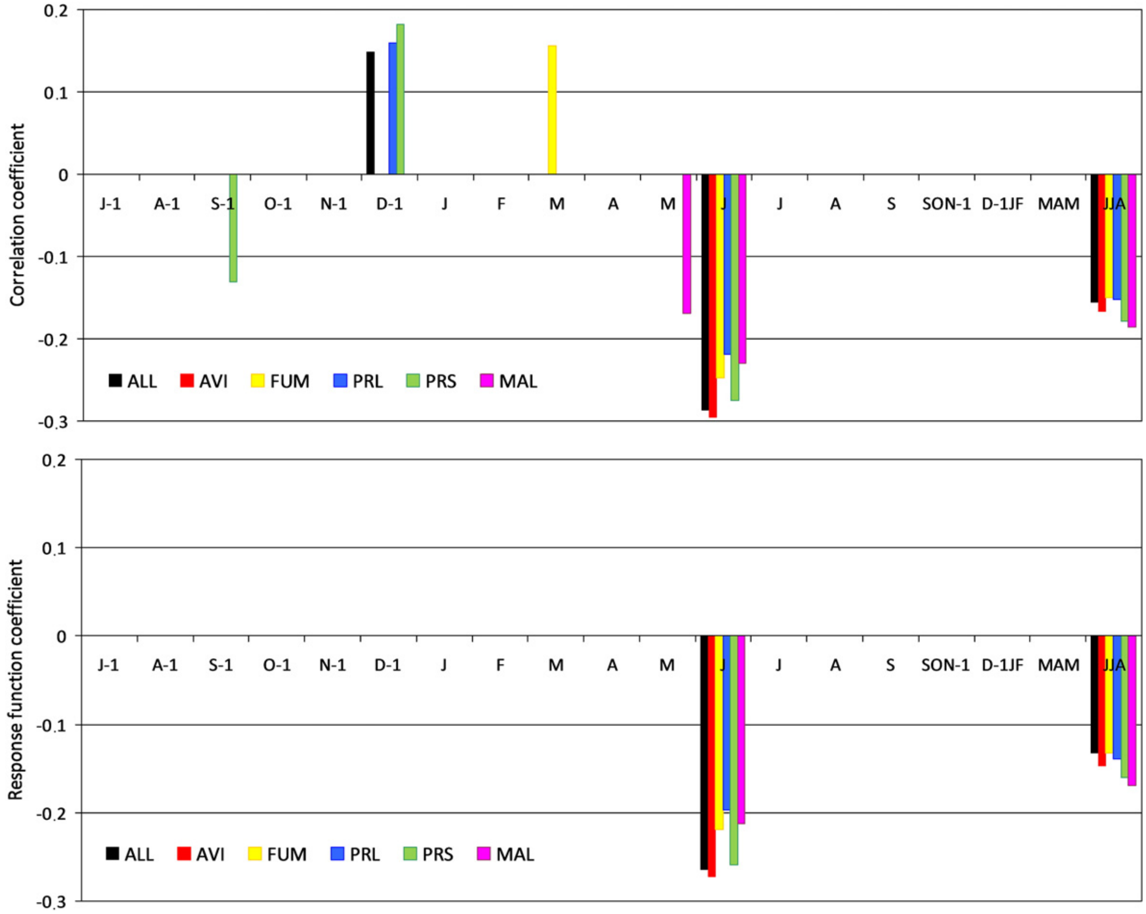

Figure 6. Correlation function (top) and response function results (bottom), coefficients are computed between the five mean site chronologies plus the ALL chronology and the monthly and seasonal precipitation variables over the time period 1878–2003. Only statistically significant correlation values are showed (significance test: 95% percentile range, $p<0.05$).

demonstrate that the change in the mechanisms driving tree-ring growth at high altitudes has probably involved conifers of different species in the same way. In our larch chronologies, the loss of the June mean temperature signal is evident over several previous decades, beginning in the 1960s.

As in Carrer and Urbinati (2006), the correlation shift is more consistent for those climate variables that primarily drive tree growth, whereas the variables with less significant impacts on ring-width growth generally show a stationary response to climate. In our tree-ring network, however, the observed non-stationary climate/tree-ring growth response also seems to be partially dependent on the mean site altitude.

Excluding the MAL chronology, which shows probable evidence of partial disturbance by non-climatic signals, the PRL chronology shows the most marked decreasing trend in the CC values for the June temperatures in the recent period compared with the other three chronologies from high-altitude sites. In particular, the PRL (1910 m a.s.l.) and PRS (2160 m a.s.l.) sites are located at the top of two adjacent valleys located in the northern sector of the APM. These sites have very similar ecological conditions and the same site aspect (NNE) but have different mean site altitudes, and the PRL chronology has the steepest decreasing trend.

The synchronous increasing trend observed in the CC values computed between the five residual chronologies and the August mean temperatures allows us to hypothesise a possible positive influence on tree growth resulting from the prolongation of the growing season. Numerous studies have reported an extension of the growing season in Europe due to the recent temperature increase (Menzel and Fabian, 1999; Sparks and Menzel, 2002; Walther et al., 2002; Menzel et al., 2006). It is probable that the effects of a prolonged growing season on tree-ring growth are particularly important at sites where temperatures represent the main limiting factor as in our study area. Moreover, our tree-ring chronologies revealed a non-linear response of tree-ring width to exceptionally high temperatures during the growing season. Extreme weather events have become more frequent in Europe during the past few decades (Klein Tank and Können, 2003), and the year 2003 was extraordinary from a climatic point of view, with the mean summer temperatures in central Europe exceeding the 1961–1990 mean by ca. 3.8°C (Beniston, 2004; Luterbacher et al., 2004; Schär et al., 2004). Particularly in temperature-sensitive environments, such as the alpine treeline, the 2003 heat wave was expected to have a strong impact on tree growth. Contrary to our expectations, we found that the larch trees in our sampling sites did not respond uniformly to the substantially warmer season by producing wider rings; only the chronologies from higher-altitude sites (PRS and AVI) featured a large 2003 ring. Leonelli et al. (2009) found a similar lack of response for a stone pine tree-ring network in the Ortles-Cevedale Group. Pilchler and Oberhuber (2007) conducted a study on *Pinus sylvestris* L. and *P. abies* L. growing in xeric conditions in a dry, inner Alpine climate (Tyrol, Austria) and found a reduction of up to 35% in radial stem growth in 2003 caused by the early interruption of cambial activity. At these low-elevation sites (ca. 750 m a.s.l.), the influence of precipitation on tree growth is more important than the influence of temperature. In particular, late spring to early summer (April–June) precipitation proved to be the environmental factor primarily associated with the radial growth of both species. Moreover, Leonelli and Pelfini (2008) found a strong growth

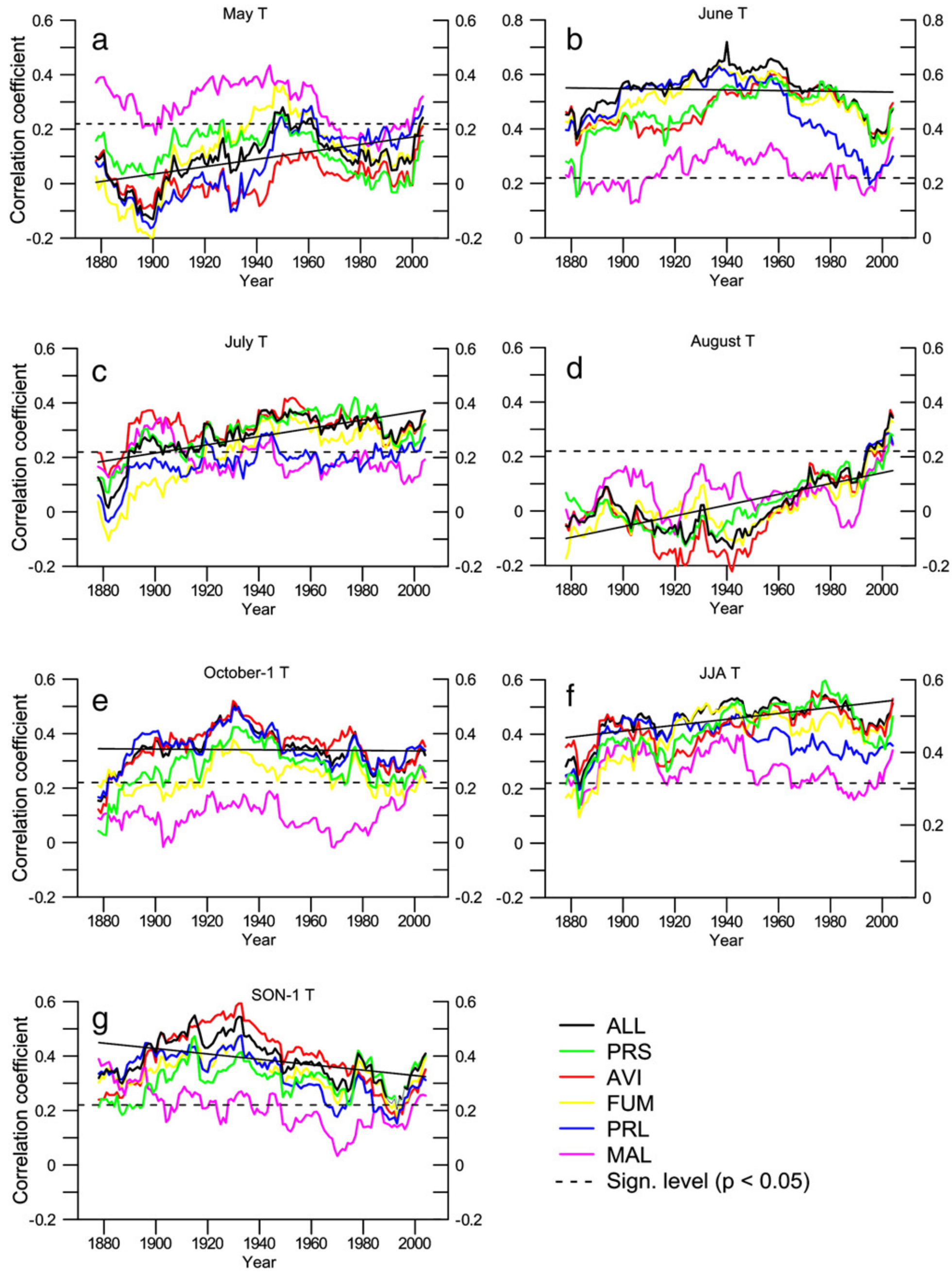

Figure 7. Moving correlation function analysis computed between the five residual chronologies, the ALL chronology, and the seasonal and monthly temperature variables for the most important months during the period 1878–2004 (significance test: 95% percentile range, $p<0.05$). The linear regression line is referred to the ALL chronology. Note the different scale of coefficient correlation values in plot (b).

reduction in 2003 in a low-altitude (1620 m a.s.l.) spruce chronology. Water stress is the most probable explanation for this finding. At our high-elevation sampling sites, precipitation is not the principal factor controlling tree growth, and the 2003 heat wave did not produce any drought stress.

Our study confirms that precipitation exerts less control on tree-ring growth than does temperature, but the MCF analysis clearly shows an increasing negative influence of June precipitation on tree-ring growth at the highest altitudes. Similar trends have been reported by Carrer and Urbinati (2006) for larch and by Leonelli et al. (2009) for stone pine. At the treeline, trees are principally fed by snow melt in early summer. Our results show that the precipitation occurring in this month is currently negatively influencing tree growth more than it has in the past and that the strongest negative influence occurs at high altitudes (e.g., the PRS chronology).

Conclusions

This study confirms that tree-ring chronologies from high-altitude sites are a useful tool for studying the temporal dynamics of climate at local and global scales. However, the response of tree-ring growth to climate parameters has varied over time. The analysis of climate/tree-ring growth relationships performed on five larch tree-ring chronologies from the top of five alpine glaciated valleys located in a singular alpine massif showed consistency, at a smaller scale, with other dendroclimatic studies conducted recently in the Alps. This analysis confirmed the presence of a common climatic signal for conifers growing at the timberline ecotone.

In the APM, as in other alpine sectors and in high-latitude areas, early summer (June and July) temperatures exert the main control on larch radial growth at the upper treeline. Although summer

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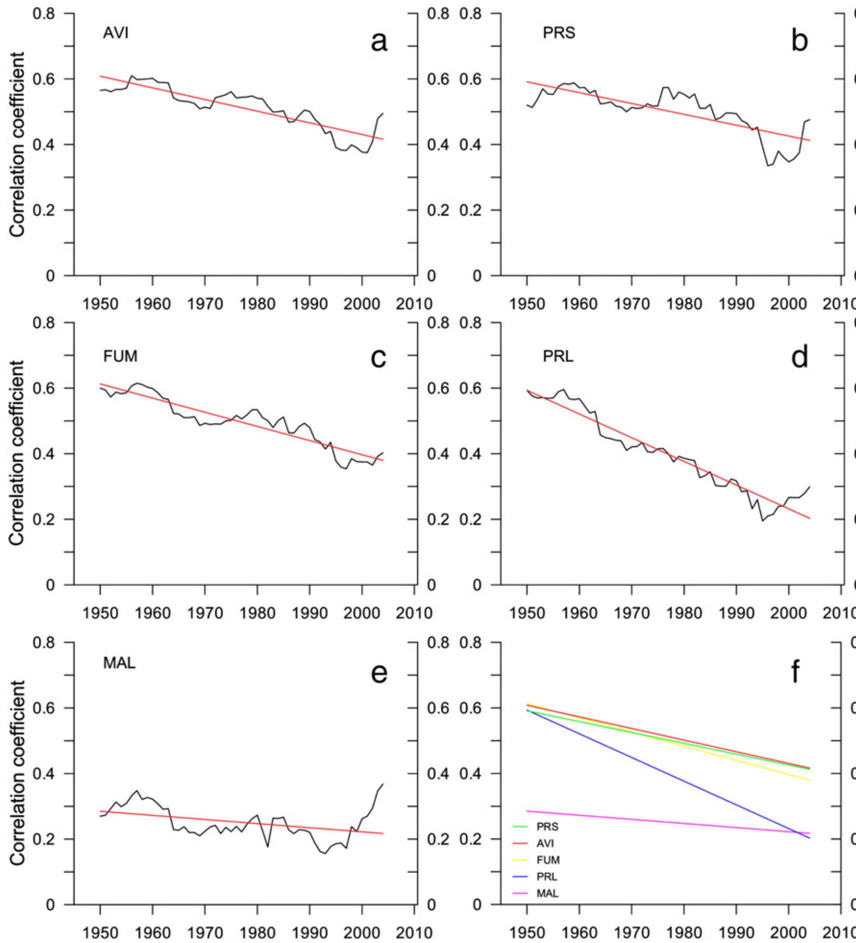

Figure 8. Trend analysis (linear trend model) conducted on June moving correlation coefficient values over the last 54 yr of analysis (1950–2004) for the five residual chronologies (a to e). Regression lines are reported in (f).

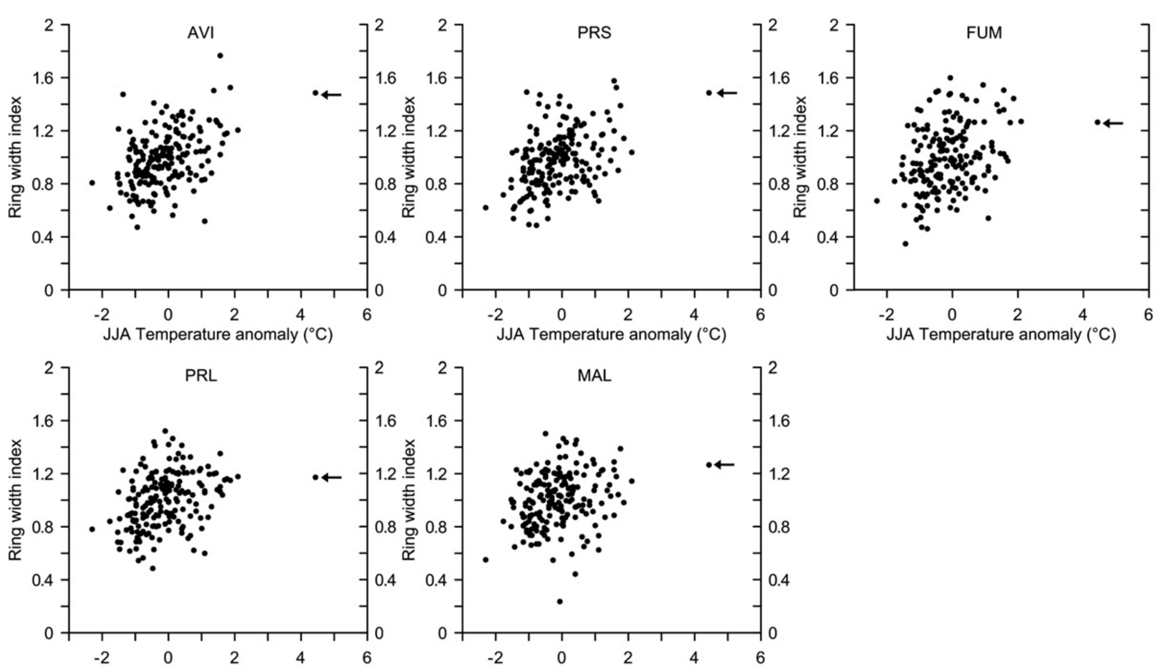

Figure 9. Scatter plot of the five residual larch chronologies vs. summer temperature anomalies over their common period (1818–2004). Arrows indicate 2003 values.

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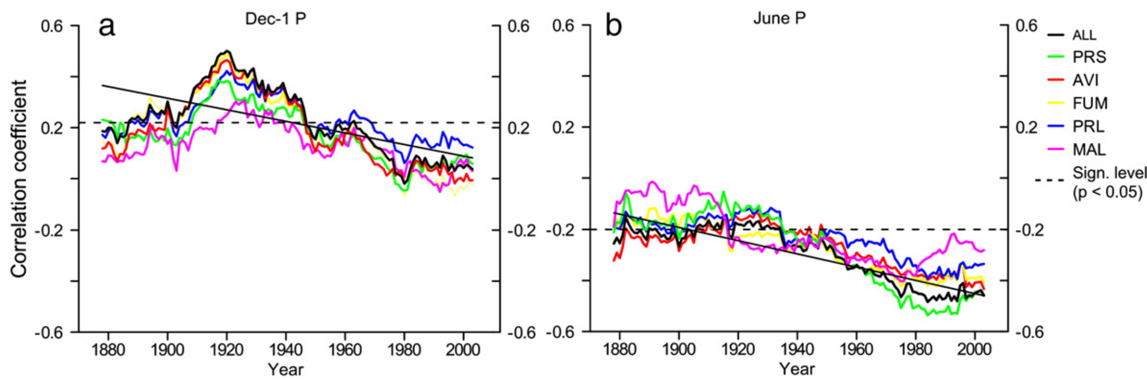

Figure 10. Moving correlation function analysis performed between the five residual chronologies, the ALL chronology, and the seasonal and monthly precipitation variables for the most important months during the period 1878–2003 (significance test: 95% percentile range, $p<0.05$). The linear regression line is referred to the ALL chronology.

temperature still limits larch growth at the timberline at our sampling sites, the MCF analysis shows a clearly visible loss of correlation between radial tree-ring growth and June mean temperatures during the past decades, especially at the low-altitude sites. In fact, even though the CC values for the MAL chronology (1850 m a.s.l.) are stable and quite low over time, the CC values of PRL (1910 m a.s.l.) changed from rather high values ($r>0.5$) to low values with a constant decreasing trend (up to $r_{min}=0.2$). The chronologies above 1990 m a.s.l. showed more stable CC values even though a decreasing trend in CC values is also recorded (r_{min} is approximately 0.4).

Overall, our results reveal a temporal instability in the climate/tree-ring response consistent to that reported in several recent studies of other sites in the Alps. According to our results, the temperature signal loss is more evident at low-altitude sites. In contrast, at high-altitude sites we found that precipitation exerts a stronger negative influence on tree growth in recent decades than in the past and has a more important role than at low altitudes. The findings of the present study indicate that even if no significant trends are present in the June precipitation record (not shown; see Leonelli et al., 2009) early summer precipitation negatively affects tree-ring growth, especially at the highest-altitude sites.

The increasing trend in the correlation values verified with the early summer (May) and August monthly temperatures allows us to hypothesise that an extended growing season affects conifer growth at our sampling sites. Overall, a weakening relationship between larch tree-ring chronologies and temperature is noticeable since the mid-20th century in the APM. Nevertheless, the high degree of climate sensitivity, the generally high values of correlation with summer temperatures, and the agreement with the results of similar studies conducted in the Italian Alps at a broader scale (e.g., Carrer and Urbinati, 2006) allow us to state that tree growth in the APM is primarily driven by temperature at high altitudes.

The Val Malga site features unique conditions, including evidence of disturbances that have affected the forest vegetation. These characteristics, also revealed by the differences found in the response of the MAL chronology to climate, lead us to exclude the MAL chronology from consideration in the context of future climate reconstructions. The other four APM larch chronologies appear to be adequate for dendroclimatic studies. The overall stable relationship between European larch tree growth and JJA temperatures suggests that high-elevation larch tree-ring data sets are suitable for climatic reconstructions.

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