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A 1052-year tree-ring proxy for Alpine summer temperatures

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Abstract A June–August Alpine temperature proxy series is developed back to AD 951 using 1,527 ring-width measurements from living trees and relict wood. The reconstruction is composed of larch data from four Alpine valleys in Switzerland and pine data from the western Austrian Alps. These regions are situated in high elevation Alpine environments where a spatially homogenous summer temperature signal exists. In an attempt to capture the full frequency range of summer temperatures over the past millennium, from inter-annual to multi-centennial scales, the regional curve standardization technique is applied to the ring width measurements. Correlations of 0.65 and 0.86 after decadal smoothing, with high elevation meteorological stations since 1864 indicate an optimal response of the RCS chronology to June–August mean temperatures. The proxy record reveals warm conditions from before AD 1000 into the thirteenth century, followed by a prolonged cool period, reaching minimum values in the 1820s, and a warming trend into the twentieth century. This latter trend and the higher frequency variations compare well with the actual high elevation temperature record. The new central Alpine proxy suggests that summer temperatures during the last decade are unprecedented over the past millennium. It also reveals significant similarities at inter-decadal to multi-centennial frequencies with large-scale temperature reconstructions, however, deviating during certain periods from H.H. Lamb‘s European/North Atlantic temperature history.

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1 Introduction

Reconstructions of longer term, regional temperature variability (e.g., Cook et al. 2003; Esper et al. 2003a; Luckman and Wilson 2005) are key to develop larger scale networks (e.g., Briffa 2000; Cook et al. 2004; Esper et al. 2002; Mann et al. 1999), assess spatial patterns of climatic change (e.g., Wanner et al. 1997), and study the influence of natural and anthropogenic forcings on temperature variations (e.g., Crowley 2000; Houghton et al. 2001). In Central Europe, significant progress has been made in reconstructing climatic variations over recent centuries (e.g., Jacobeit et al. 2003) including analyses of long instrumental records (Böhm et al. 2001; Camuffo and Jones 2002; Jones and Lister 2004; Moberg et al. 2003), documentary evidence (Brázdil 1996; Glaser 2001; Pfister 1999), tree-ring records (Briffa et al. 2002a, b) and multi-proxy compilations (Casty et al. 2005; Luterbacher et al. 2004). For the Alps, several dendroclimatic studies assessed temperature signals in local tree-ring chronologies (Carrer and Urbinati 2001, 2004; Meyer and Bräker 2001; Rolland et al. 2000; Wilson and Topham 2004) and regional scale networks (Briffa et al. 1988; Frank and Esper 2005a, b; Rolland 2002; Schweingruber and Nogler 2003) spanning the past couple of centuries. However, a millennial-long, high-resolution Alpine temperature reconstruction that could potentially place the recent warming trend in a longer term context, and would allow a comparison with conditions during the putative medieval warm period (Lamb 1965) is broadly missing.

The lack of millennium-long tree-ring based temperature reconstructions is related to the relatively low, maximum tree ages commonly reached in the Alps (Eckstein 1982) and the difficulty in finding sub-fossil wood (Holzhauser 2002; Nicolussi and Patzelt 2000). Here, we attempt to overcome these difficulties by combining data from living trees with those from dry-dead and sub-fossil wood (Nicolussi and Schießling 2002) together with dendroarchaeological sources (Büntgen et al. 2004, 2005). This is done for five central Alpine valleys using samples of larch (*Larix decidua* Mill.) and stone pine (*Pinus cembra* L.) from elevations >1,500 m a.s.l., where summer temperature is the main limiting factor for many Alpine tree species (Frank and Esper 2005a). The resulting chronologies cover the past millennium and allow the assessment of long-term temperature trends for the Alps.

In Sect. 2, the compiled dataset from living trees and historical timber is introduced. Individual ring width measurements are first standardized using traditional detrending methods to retain multi-decadal and higher frequency variations (Fritts 1976) and combined on a valley-by-valley basis. In Sect. 3.1, it is demonstrated that the four larch datasets share a strong common signal and are merged for further analyses. In Sect. 3.2, the tree-ring data are then detrended using the regional curve standardization method (RCS, Becker et al. 1995; Briffa et al. 1992, 1996; Esper et al. 2003b; Mitchell 1967), which may help to preserve long-term, millennial-length trends in resulting chronologies. The larch and pine RCS chronologies are then combined to maximize the sample size and improve the climate response. In Sect. 3.3, the climatic signal of the 1,052-year composite larch/pine chronology is assessed by calibration with high elevation instrumental temperature measurements. A discussion of the new record, and comparison with other regional (European), and large-scale (Northern Hemisphere) proxy reconstructions are provided in Sect. 4.

2 Data and methods

We have compiled the largest dataset of living and relict, high elevation wood samples so far used to reconstruct Alpine temperature variations for the last millennium (Table 1). Samples include four larch chronologies from Switzerland and the most recent part of a 7,000-year pine chronology from Austria. All sites are within the 46°28′–47°00′N and 7°49′–11°30′E region (Fig. 1). In total, 1,110 *Larix decidua* and 417 *Pinus cembra* ring width series, all from locations >1,500 m a.s.l., are integrated. For the larch collection, the precise number of trees represented by these 'series' is, however, not specified, since some of the old beams used in this study might originate from the same trees. For pine, each 'series' represents a single tree.

Larch trees were sampled, measured and cross-dated by U. Büntgen and M. Schmidhalter for the Lötschental (LOE-L), by M. Schmidhalter for the Goms (GOM-L) and Simplon region (SIM-L), and by M. Seifert and co-workers for the Engadine (ENG-L), and represent so-called 'composite datasets', i.e., compilations of data from living trees and historical buildings. Pine trees were sampled and processed by K. Nicolussi and co-workers for western–central Austria (AUT-P), integrating material from living trees and dry-dead and sub-fossil logs from moraines and sediments. The start dates of these datasets range between AD 505 and 1085, and end dates between 1993 and 2003 (Table 1). The numbers of series per dataset varies considerably from 78 (SIM-L) to 417 (AUT-P), affecting the development of regional chronologies of comparable signal strength characteristics (Fritts 1976). The mean segment length (MSL)—the average number of rings per core or disc sample—ranges from 129 years (GOM-L) to 259 (SIM-L), with a grand mean of 186 years. These numbers are relevant when individual series detrending methods are applied, since climatic information on wavelength longer than the series' segment length are not retained (details in Cook et al. 1995).

Prior to detrending, all measurements were re-checked for missing rings and dating errors on a site-by-site basis using the program COFECHA (Holmes 1983). Missing and exceptionally narrow rings, likely caused by larch budmoth (LBM, *Zeiraphera diniana* Guénée) outbreaks (Baltensweiler and Rubli 1999; Rolland et al. 2001; Weber 1997), were set to a value of 0.1 mm. This was done to handle the varying treatment of missing rings between the labs involved in this study, as they used differing values to fill in tree-ring measurements. The number of values changed this way is 0.82% (no. 2,163) of the total number of rings (no. 264,879) (Table 1; up-valuing). The procedure also minimizes the effect of non-climatic (negative) outliers due to defoliation on resulting chronologies.

Table 1 Tree-ring data, characteristics and sources

	Lat/Long	Species	Series no.	Period	MSL	AGR	Up-valuing (%)	Source
LOE-L	46°26′/7°49′	LADE	330	1085–2002	201	0.86	1.58	Büntgen/Schmidhalter
GOM-L	46°26′/8°11′	LADE	326	505–2003	129	1.04	0.87	Schmidhalter
SIM-L	46°12′/8°04′	LADE	78	685–2003	259	0.87	1.19	Schmidhalter
ENG-L	46°28′/9°47′	LADE	376	800–1993	144	1.15	0.93	Seifert
AUT-P	46°00′/11°30′	PICE	417	645–1997	197	0.99	0.00	Nicolusi
Total			1527	505–2003	186	0.96	0.82	

Period total length without truncation *MSL* mean segment length (years) *AGR* average growth rate (mm)

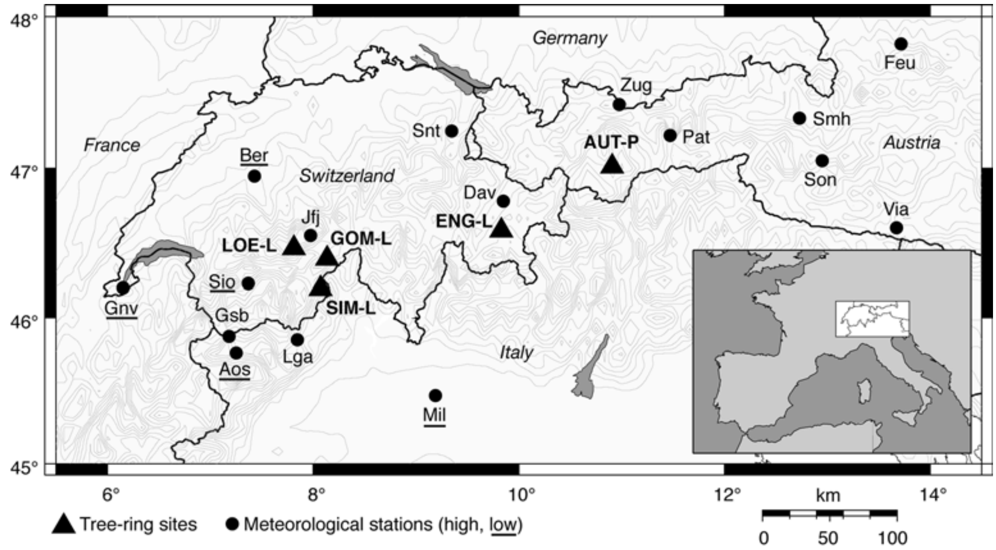

Fig. 1 Locations of 11 high and five low elevation meteorological stations (Böhm et al. 2001), and regional ring width datasets. High elevation stations (>1,500 m a.s.l.): *Dav* Davos (1901), *Feu* Feuerkogel (1930), *Gsb* Gr. St. Bernhard (1818), *Jfj* Jungfraujoch (1933), *Lga* Lago Gabiet (1928), *Pat* Patscherkofel (1931), *Smh* Schmittenhöhe (1880), *Snt* Säntis (1864), *Son* Sonnenblick (1887), *Via* Villacher Alpe (1851), *Zug* Zugspitze (1901). Low elevation stations (<600 m a.s.l.): *Aos* Aosta (1841), *Ber* Bern (1864), *Gnv* Geneva (1760), *Mil* Milano (1763), *Sio* Sion (1864). *Parentheses* denoted start years of instrumental measurements ending in 2002. Tree-ring collections: *LOE-L* Lötschental, *SIM-L* Simplon, *GOM-L* Goms, *ENG-L* Engadine (all larch); *AUT-P* Western Austria (pine)

For detrending, two conceptually different standardization methods were applied:

(a) To emphasize inter-decadal and higher frequency variations, 300-year splines (Cook and Peters 1981) were fit to power transformed (Cook and Peters 1997) individual measurements, and residuals between the measurements and splines calculated. Resulting chronologies are used for regional comparisons and to assess the merging of the regional data.
(b) To preserve common inter-decadal and lower frequency variations, Regional Curve Standardization (RCS) was applied (Becker et al. 1995; Briffa et al. 1992, 1996; Esper et al. 2003b; Mitchell 1967). This is a so-called age-dependent composite detrending method, where (1) a given number of power transformed measurements are aligned by cambial age, (2) a single growth function [regional curve (RC), smoothed using a spline function of 10% the series length] is fit to the mean of all age-aligned measurements, and (3) the deviations of the measurements from this smoothed growth function are calculated as residuals (details in Esper et al. 2003b).

All detrended series were averaged to chronologies using the biweight robust mean (Cook and Kairiukstis 1990). The variance was stabilized to minimize the effect of changing sample size using a technique that considers the number of samples per year and the cross-correlation between the single measurements (Osborn et al. 1997). Chronologies were truncated at <5 series to eliminate weakly replicated portions.

To avoid end-effect problems in smoothed records, we padded the chronology ends using the mean of the chronology values at the (truncated) ends (Mann 2004). Uncertainty in the final larch/pine composite chronology is calculated by averaging the 95% bootstrap confidence intervals (CI) (Efron 1987) obtained for each species.

For the calibration of proxy data, 11 high elevation meteorological station records are used (Böhm et al. 2001). The common period of the homogenized station data is 1933–2002, with three stations reaching back to 1864. Common period correlation coefficients using June–August (JJA) mean temperatures range from 0.71 to 0.95, demonstrating a rather homogenous temperature field over the study area (Böhm et al. 2001; Frank and Esper 2005a, b). The 11 high elevation stations are located in ‘rural’ settings above 1,500 m a.s.l. spanning most of the Alpine arc (Fig. 1). To further extend the period of overlap with proxy data back in time, instrumental data from five low elevation stations, with one of them reaching back to 1760 (Geneva), are considered.

Split calibration and verification periods are applied to assess the temporal stability of the model, using the Pearson’s correlation coefficient (r), the reduction of error (RE), coefficient of efficiency (CE), and Durbin–Watson statistic (DW) applied to the regression residuals (Cook et al. 1994; Fritts 1976). The RE and CE statistics test whether the model provides a more skillful estimate than the mean climatology of the calibration and verification periods, respectively, with positive values indicating skill of the regression model. The DW statistic

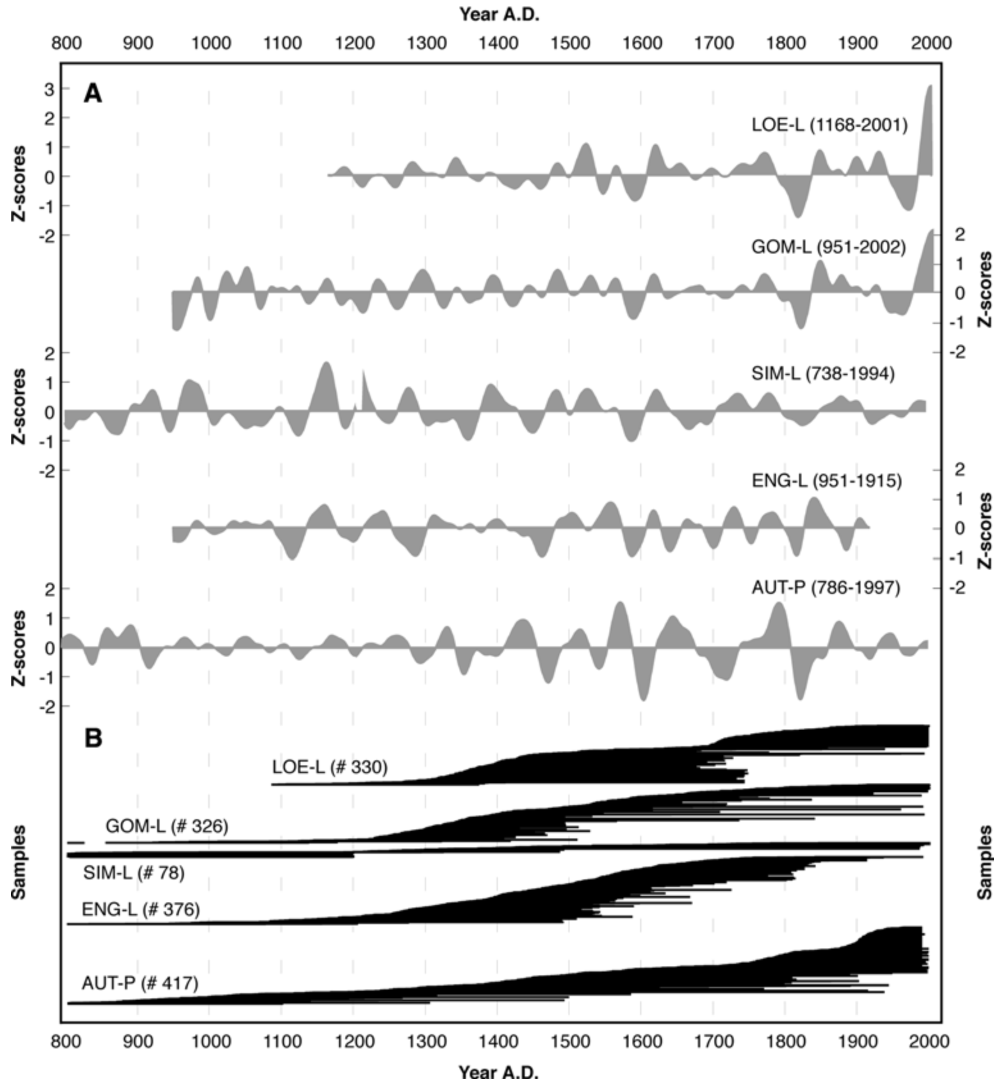

Fig. 2 **a** Regional ring width chronologies detrended using 300-year spline fittings. Chronologies are truncated at a sample size < 5 series. *Numbers in parentheses* indicate the length of the records (note the 1201–1211 gap in SIM-L, where sample replication falls below five series). Records smoothed with a 20-year low-pass filter for illustration. **b** Sample distribution of the chronologies, with each *bar* representing a single series

tests for autocorrelation in the residuals between model and target climate data.

3 Results

3.1 Inter-decadal variations

The spline detrended regional larch (LOE-L, GOM-L, SIM-L, ENG-L), and the pine (AUT-P) chronologies reveal inter-decadal scale growth variations over the past millennium (Fig. 2a). The records rely on varying numbers of tree samples that are also differently distributed over the past millennium (Fig. 2b). After truncation at a minimum sample replication of < 5 series, only two of the regional chronologies (LOE-L, GOM-L) reach into the twentyfirst century.

The smoothed chronologies show periods of similar inter-decadal fluctuations, with low values ~1450–1470, ~1580–1600, and the 1820s, and positive variations ~1150–1170, ~1610–1620, and the 1780s, for example (Fig. 2a). Interestingly, during the Late Maunder Minimum 1675–1715 (Luterbacher et al. 2001; Pfister 1999; Wanner et al. 2000) only the AUT-P chronology shows a prominent, multi-decadal growth reduction, whereas ENG-L and SIM-L indicate a shorter and slighter reduction, and LOE-L and GOM-L approximately average growth. The most distinct period of low values is centered around 1820, where all chronologies indicate reduced growth rates. This depression is also reported from a high elevation network analysis including four species (fir, larch, pine and spruce) from 53 high elevation tree sites in the Alps (Frank and Esper 2005b). The period is characterized by Alpine glacier advances (Holzhauser 2002; Nicolussi and Patzelt 2000), reduced solar irradiance (Dalton Minimum), and major volcanic eruptions, in 1809 (unknown), 1813 (Awu, Soufriere St. Vincent, Suwanose–Jima) and 1815 (Tambora), resulting in a pronounced cooling of summer temperatures over the Northern Hemisphere (Briffa et al. 1998; Cole-Dai et al. 1997; Grove 1988).

Temporal changes in variability are observed in the chronologies. For example, the LOE-L variability is reduced until about 1500 followed by larger variations until present (Fig. 2a). A similar period of reduced variability is evident in AUT-P from ~950 to 1400. These variability changes, also visible in the unsmoothed chronologies (Fig. 3a, c), might partly be related to transitions between different populations, e.g., living/historic, historic/historic, sub-fossil/dry-dead, causing variations in site conditions and differing age structures. The feature is, however, not consistent along the dataset, and requires further research to be fully understood.

Common variance is notably higher between the larch chronologies than the larch and pine data (Table 2), but seems also to be influenced by the relative position of tree sites (Fig. 1). Highest correlation is found between LOE-L and GOM-L, reflecting their proximal locations and shared species. Lowest correlation occurs between AUT-P and SIM-L, likely influenced by the distance between sampling regions, species differences and the low sample replication of SIM-L.

The average cross-chronology correlation $\bar{r}$ between the larch records is 0.47 over the 1212–1915 common period, and ranges from 0.15 to 0.72 for 50-year segments (Fig. 3b). Interestingly, the larch $\bar{r}$ values computed before and after 1340 are 0.34 and 0.54, respectively, indicate a reduction in common variance back in time. This finding is further supported by running calculations of the expressed population signal (EPS) for each regional chronology (Fig. 3d). The EPS statistic expresses the signal strength of a chronology with respect to that of the theoretical 'population signal' (details in Wigley et al. 1984). It indicates fairly robust signals back to about the thirteenth century for the regional chronologies. EPS values of the mean chronology using all larch (Fig. 3d; ALL-L) and pine data (AUT-P), however, exceed the widely applied 0.85 threshold (Briffa and Jones 1990) back to 951, the period from which at least four regional chronologies (after truncation) are available (see vertical dashed line in Fig. 3), indicating that the records from both species provide temporally stable signal strength statistics at least over the past millennium.

3.2 Low frequency variations

To preserve low frequency, multi-centennial trends over the past millennium, RCS was applied to the larch, and pine dataset. For the 1,110 larch series, a single RC was estimated and one RCS run calculated (details in Briffa et al. 1992, 1996; Esper et al. 2003b; Melvin 2004). The pine data, however, were 'horizontally' split into groups representing samples from living (no. 232) and relict (no. 185) trees, as these sub-samples considerably differ in mean growth rates of 1.26 and 0.65 mm, and mean segment length of 153 and 253 years, respectively, and two RCS runs calculated (Nicolussi et al. 2005). The

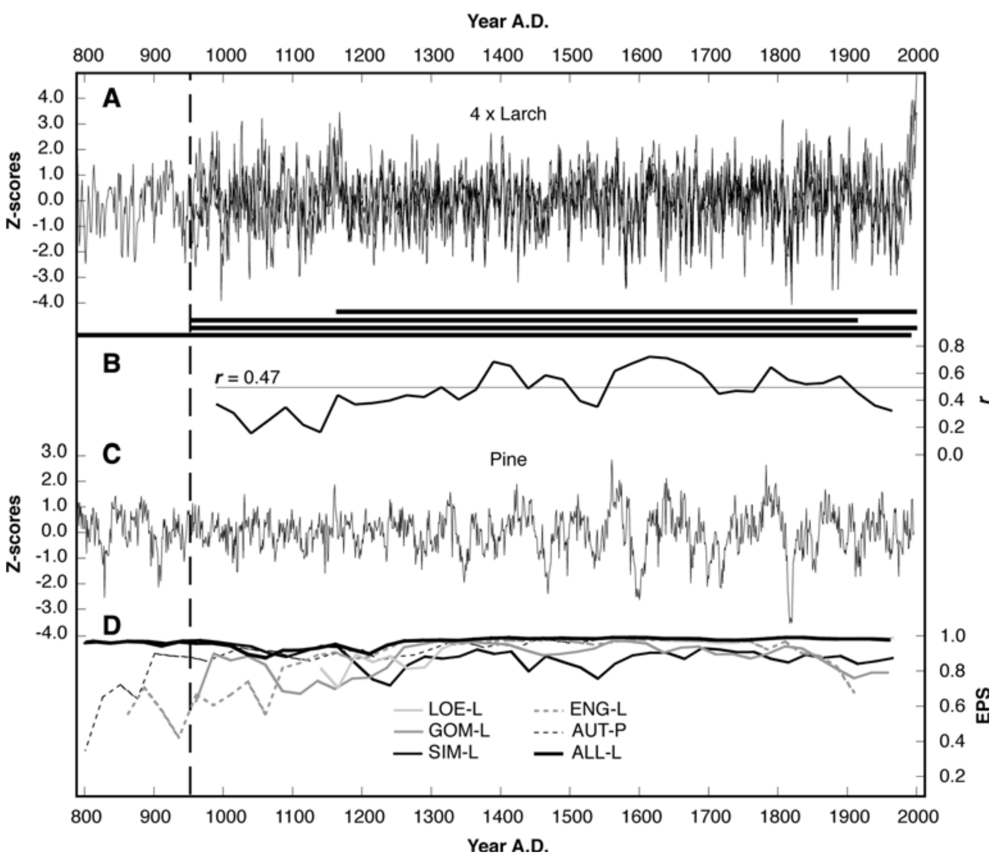

Fig. 3 Three hundred year spline-detrended chronologies and signal strength statistics. **a** Four larch chronologies and periods covered by these records (*horizontal bars*). **B** Average cross-chronology correlation *r* of the four larch records calculated for 50-year periods (offset is 25 years). **c** Spline-detrended pine chronology. **d** EPS statistics (Wigley et al. 1984) of the regional site chronologies and a chronology using all larch data, calculated for 50-year periods (offset is 25 years). The *vertical dashed line* in 951 indicates the period covered by four regional chronologies, with reasonable signal strength statistics in the ALL-L and AUT-P chronologies

Table 2 Correlation matrix of the spline detrended chronologies (1212–1915 period)

	LOE-L	GOM-L	SIM-L	ENG-L	AUT-P
LOE-L		0.74	0.42	0.32	0.26
GOM-L	0.77		0.40	0.38	0.13
SIM-L	0.53	0.56		0.18	0.10
ENG-L	0.46	0.54	0.38		0.21
AUT-P	0.22	0.19	0.15	0.35	

Results of the original and 40-year smoothed chronologies are shown in the left/lower and right/upper part of the matrix, respectively. After correction for lag-1 autocorrelation, all correlations of the unfiltered data reach the 99.9% significance level. After smoothing, only the correlation between LOE-L and GOM-L reaches the 95% significance level

resulting pine chronologies cover the 645–1946 and 1541–1997 periods, and the correlation of these records over the well-replicated 1700–1900 period of overlap is 0.86. During this period, each dataset has six or more series with a combined sample size always greater than 71 series.

The average of the two pine RCS chronologies, weighted by the number of series, is shown together with the larch RCS chronology (Fig. 4a). Over the 951–1997 common period, the larch and pine records correlate at 0.39, and 0.51–0.57 after smoothing the records with 60, 80, 100, and 120-year low-pass filters. With respect to the shared variance and the increased temperature signal, we provide an unweighted mean of the larch and pine chronologies (Fig. 4b). The combined record is also accompanied with annual 95% confidence limits (approximately ±2SE) computed separately for the larch and pine chronologies, then averaged and smoothed with a 20-year low-pass filter.

In comparison to the spline detrended records (Fig. 2a, 3a, c), the RCS chronologies possess more low frequency variability over the last millennium. The chronologies from both species show a period of high index values from the beginning of the millennium into the thirteenth century. This period, and the high values since ~1850, frame a period of lower chronology levels from about the fourteenth century until the early nineteenth century. Most pronounced during this period of low values, are pulses of increased growth rates in the late sixteenth century in the pine data, and the mid eighteenth century in the larch data. Before 1000, when sample replication is low in both datasets, the larch RCS chronology possesses substantially higher values than the pine chronology, indicating uncertainty during this period. The long-term trends found in both species mirror the putative Medieval Warm Period (Broecker 2001; Esper et al. 2002; Lamb 1965) at the beginning of the last millennium, followed by the Little Ice Age (Grove 1988) and recent warming (Houghton et al. 2001) since about the mid-nineteenth century.

To further explore, the strength of the low frequency signal in the RCS chronologies, the multi-site larch data, combining a total of 1,110 measurements, are split into several sub-groups according to (1) geographic region, Valais and Engadine, (2) segment length, <150/150–250/>250 years, and (3) pith offset information, i.e., samples including and not including the innermost ring (Fig. 5a–c). The number of samples of these sub-groups are, however, significantly reduced in comparison to the calculation using all larch data, affecting the establishment of a robust RC (Fig. 5d), and adding uncertainty to the resulting RCS chronologies, particularly during low replication periods (displayed in Fig. 5a–c) where only a few measurements remain.

Largest differences between the split RCS chronologies are recorded before ~1300 and after ~1800.

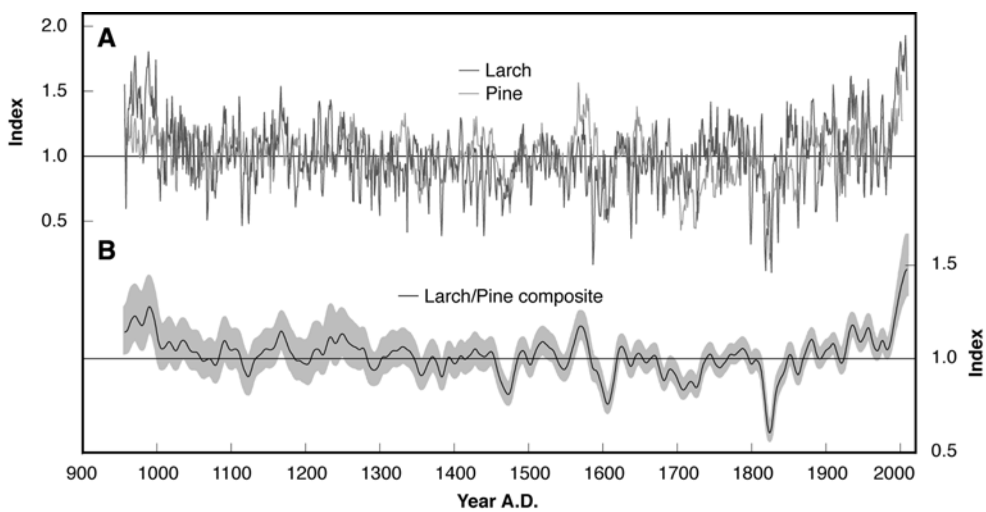

Fig. 4 **a** Comparison of the RCS detrended larch and pine chronologies since 951, and **b** the arithmetic mean of these records, smoothed using a 20-year low-pass filter. *Shaded envelopes* indicate the approximate 95% CI

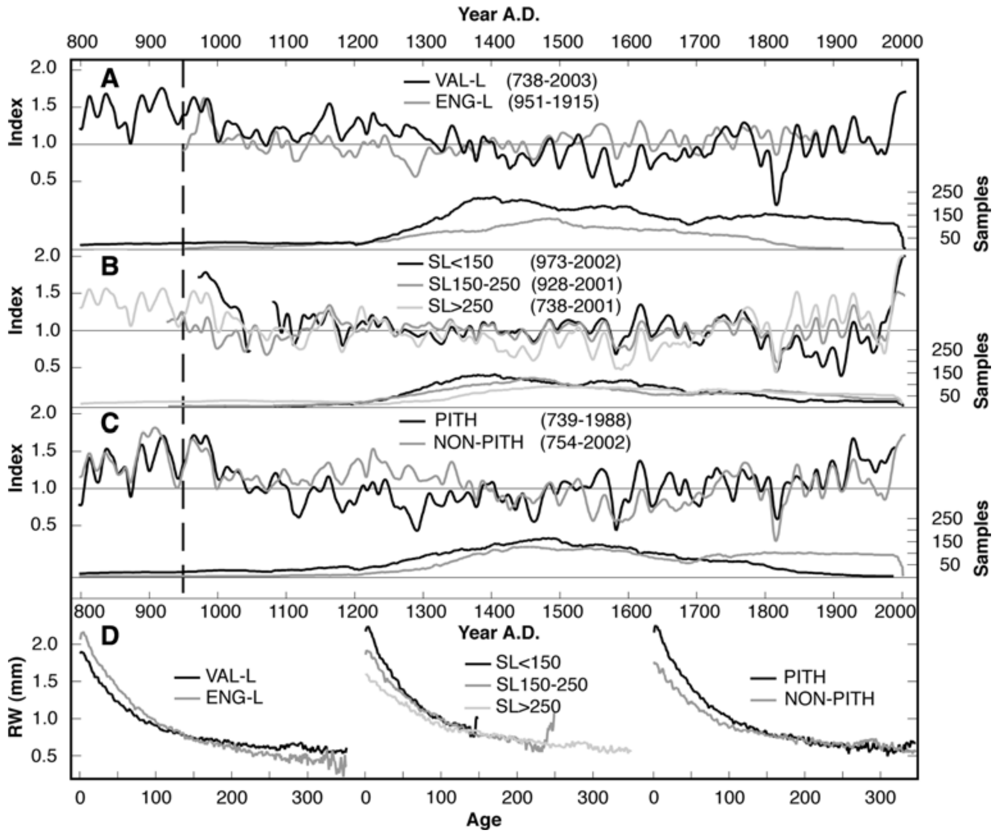

Fig. 5 RCS chronologies derived after splitting the larch data (1110 series) into **a** the regions 'Valais' (734) and 'Engadine' (376), **b** series with segment length <150 years (614), series with SL 150–250 years (312), series with SL>250 years (184), and **c** series including the pith (518) and series with pith offset (396). Sample replications are indicated at the bottom of **a**–**c**. **d** Average growth curves (RC) of the age-aligned data after splitting

Considerable uncertainty during the period ~1100–1300 is found between the Valais and Engadine data, and the pith and non-pith sub-groups, with the latter reaching well into the fourteenth century. The splitting into three segment length sub-groups indicates increased variance from ~1830 until the middle of the twentieth century, and before ~1150, adding additional uncertainty, during these periods, to the larch RCS chronology and the combined record using both larch and pine data (Fig. 4). These uncertainties stem at least partly from systematic changes in the RC of the split sub-groups—i.e., shorter segment lengths and samples including the pith show higher growth rates in young age-classes, for example (Fig. 5d)—and the seemingly uneven distribution of the samples of these categories over the past millennium (for details see Esper et al. 2003b; Melvin 2004).

3.3 Climate signal

Correlation analyses using homogenized monthly and seasonal high elevation instrumental station data (Böhm et al. 2001) reveal a response maximum to June–August (JJA) mean temperatures in the ring width data (Fig. 6a). Calculated over the 1864–1997 period, correlations from previous year May to current year September monthly temperatures show similar growth/climate response patterns for larch and pine, with the pine trees being slightly more sensitive, and their unweighted mean yielding a stronger signal than obtainable from either chronology alone.

For the combined larch/pine data, correlations with JJA temperature increase to 0.64 and 0.86 after decadal smoothing (1864–2002) both exceeding the 99.9% significance level after correction for lag-1 autocorrelation (Trenberth 1984).

To assess the temporal stability of the climatic signal, split period calibration/verification tests are applied (Fig. 6, inset tables), using the Pearson correlation coefficient (r), reduction of error (RE), coefficient of efficiency (CE), and Durbin–Watson statistics (DW) (Cook et al. 1994; Fritts 1976). Results for the 1864–1933 and 1934–2002 periods are $r=0.63$ and 0.60, $RE=0.43$ and 0.46, and $CE=-0.20$ and -0.05, respectively. DW values are all above 1.71 indicating insignificant trend in the model residuals. After decadal smoothing, $r=0.90$ and 0.89 for the calibration and verification periods, respectively.

These calibration and verification statistics suggest that the combined larch/pine tree-ring width data can be used to reconstruct summer temperatures. However, the negative CE values indicate a loss of reconstruction skill, particularly in the lower frequency domain. This loss is further documented by the trend difference between proxy and early low elevation instrumental data back to 1760 (Fig. 6b), with the station data indicating substantially warmer JJA temperatures before 1860. Also the calibration results against these early measurements are substantially lower, with $r=0.35$ and 0.48 (1760–

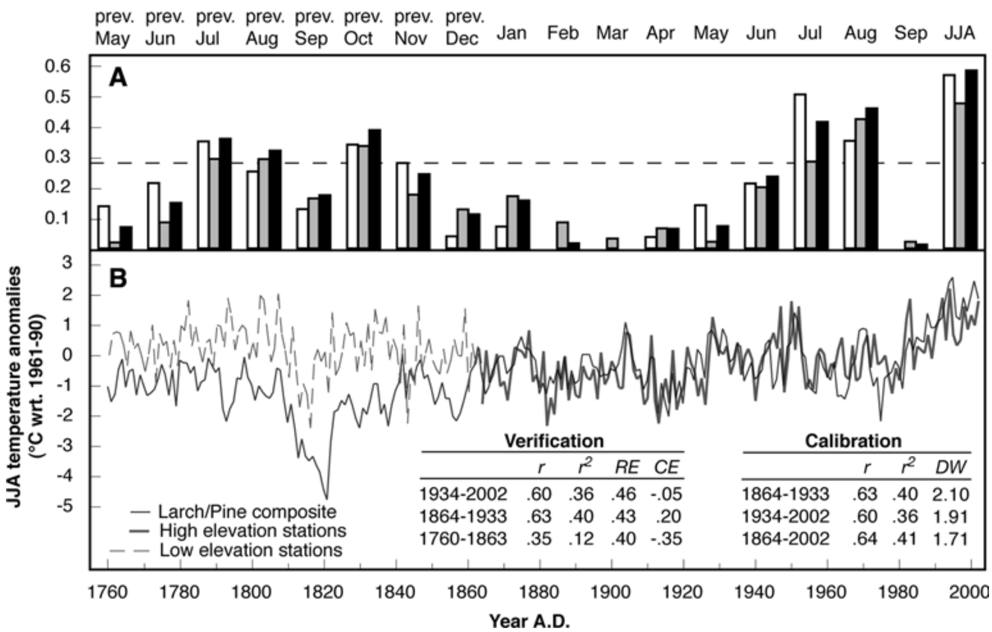

Fig. 6 **a** Correlations of the RCS detrended pine (*white*) and larch (*grey*) chronologies, and their combination (*black*), with monthly mean temperatures of the previous and current year, calculated over the 1864–1997 common period. The *dashed line* denotes the 99.9% significance level, corrected for lag-1 autocorrelation. **b** The RCS larch/pine composite record together with JJA temperatures from high elevation (back to 1864) and low elevation stations (back to 1760). *Insert tables* show the calibration and verification statistics against JJA temperatures of the current year, with *r* correlation coefficient, r^2 explained variance, *RE* reduction of error, *CE* coefficient of efficiency, and *DW* Durbin–Watson statistics

1863 period) for the original and smoothed records, respectively.

Possible explanations for the divergence with early instrumental data are discussed below. To avoid potential bias in the transfer of the proxy data, the full period of overlap with the high elevation JJA temperature data (1864–2002) is considered for calibration using linear regression (Fig. 6).

4 Discussion

4.1 Alpine climate history

The combined larch/pine summer temperature proxy provides evidence for warm conditions during the first three centuries of the last millennium (Fig. 4b). This period, associated with the Medieval Warm Period, is characterized by significant inter-decadal temperature variations, with warm decades centered around 1160 and 1240. High summer temperatures are also inferred prior to AD 1000, but caution with this observation is warranted as this period is characterized by low sample replication (Fig. 2b) and notable differences between the larch and pine data (Fig. 4a).

Between ~1350 and 1850, an extended period associated with the Little Ice Age, the new reconstruction indicates generally cooler conditions, accompanied by significant inter-decadal variations. Key fluctuations are low temperatures in the 1350s, 1460s, ~1600, around 1700 and 1815–1820, and high temperatures in the 1570s. Interestingly, the warmth during the 1570s, which is more pronounced in the pine than the larch data (Fig. 4a), is only exceeded prior to AD 1000 and the recent decade.

Since the 1820s, temperatures increased until the end of the record in 2002. This trend and the inter-decadal variations seen since 1864 are in line with JJA temperatures recorded in the Alps (Fig. 6b and 7a). Overall, the proxy record suggests that temperatures during the last decade are unprecedented over the past 1,052 years in the Alps. This conclusion is derived from tree-ring data, and not by splicing instrumental measurements to lengthen the proxy record until 2002 (e.g., Cook et al. 2004; Mann et al. 1999). However, the significance of this notion is limited, since the number of chronologies and samples is reduced in recent years (Fig. 2).

The mean JJA temperature signal of the reconstruction (Fig. 6) increases after smoothing the data using a 10-year low-pass filter. Several studies have detailed the climatic sensitivity of high elevation larch wood (e.g., Carrer and Urbinati 2001, 2004; Rolland et al. 1998; Serre 1978). Recently, Frank and Esper (2005a, b) described the potential of this species for Alpine temperature reconstructions, and present evidence for a dominant response to JJA summer temperatures, which often is as strong as for most other conifers, seemingly despite the periodic (8–9 years) defoliation due to larch budmoth (LBM, *Zeiraphera diniana* Guénée) outbreaks (Baltensweiler and Rubli 1999; Rolland et al. 2001; Weber 1997). These events cause reductions in radial growth of larch trees, affecting the climatic signal particularly in the higher frequency, inter-annual domain. Consequently, decadal smoothing of the ring width record presented here reduces the LBM effect and correlations increase from 0.64 to 0.86. We are currently developing a millennial-long maximum latewood density record from larch wood to further study the impact of LBM on the high frequency climatic signal.

The comparison with early low elevation data before 1864 indicates an offset between (warmer) instrumental and (cooler) proxy data (Fig. 6b). This offset could potentially be related to the (1) homogenization applied to early instrumental measurements, (2) season captured

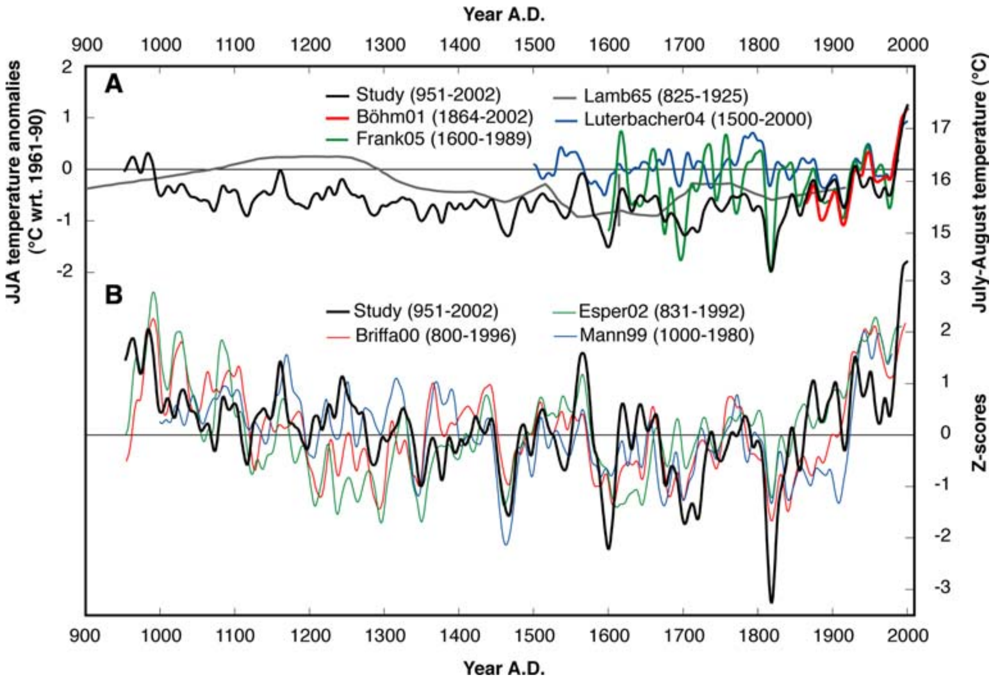

Fig. 7 Comparison of regional and large-scale temperature reconstructions. **a** The new Alpine RCS detrended record, combining larch and pine data, together with the JJA reconstruction of Frank and Esper (2005b), the JJA reconstruction of Luterbacher et al. (2004) and the reconstruction of Lamb (1965), and the JJA high elevation instrumental temperatures from Böhm et al. (2001). The original records were adjusted to have the same mean during the 1961–1990 period, except for Lamb65, which refers to July–August mean temperatures (see axis on the right). **b** The Alpine larch/pine RCS reconstruction together with large-scale records representing the Northern Hemisphere (Mann et al. 1999, multi-proxy), the Northern Hemisphere extra-tropics (Esper et al. 2002, tree-rings) and the latitudinal band north of 60°N (Briffa 2000, tree-rings). Mann99 is likely weighted towards annual, and Esper02 and Briffa00 towards warm season temperatures. Records are normalized over the 1000–1980 common period. Except for Lamb65, all records are smoothed using a 20-year spline and padded using the mean of the last ten values at both ends

by the tree-ring data, (3) elevation difference between proxy sites and instrumental stations, and/or (4) temporal changes in tree-site ecology and population.

1. Less replicated and more insecure temperature data before ~1850 (Böhm et al. 2001), with only the Geneva and Milano stations south of the Alps reaching back to 1760 and 1763, respectively (Fig. 1), could potentially explain the offset between observations and proxy. Interestingly, the adjustments performed during homogenization resulted in an increase of summer temperatures before about 1850, followed by a cooling of stations until about the middle of the twentieth century (Böhm et al. 2001). Other re-adjustment studies, e.g., from Scandinavia using long cloud cover records, suggest that early summer season temperatures are too warm (Moberg et al. 2003). Such changes would perhaps only partly explain the quite substantial offset with the proxy record. We intend to analyze this offset more closely by fitting tree-ring based reconstructions to differently homogenized and basically raw instrumental data.
2. Another explanation for the offset between proxy and instrumental data is related to the seasonality of climate response of high elevation *Larix decidua* and *Pinus cembra* trees that is not strictly limited to current year summer temperatures (Fig. 6a). This finding is in line with evidence from other timberline environments indicating substantial effects from seasons before the vegetation period and even previous years (Fritts 1976). Comparisons of Alpine tree-ring records with annual temperatures recorded in long instrumental station data, that are significantly cooler than the summer season temperatures before 1850, demonstrate that the reconstructions match long-term annual temperature trends more closely than summer season averages (Frank and Esper 2005b).
3. A more general limitation of the significance of the offset between proxy and early instrumental data is the elevation difference between tree sites and low elevation stations. For the Alps and surrounding areas, elevation differences affect the correlation between instrumental stations more substantially, than their horizontal separation (Böhm et al. 2001), making the low elevation grid less representative for findings in high elevation environments.
4. Finally, potential systematic differences in site ecology between the living and historic trees (e.g., growth rates of the historic trees are reduced because of relatively higher stresses in boundary environments), could explain the offset with early instrumental

measurements, particular when the origin of historical material is not exactly known. This explanation is limited, however, since the majority of living trees span the last 300 years and most of the historical samples do not stretch into the nineteenth century (Fig. 2b).

For the current study, it seems noteworthy that a possible calibration including early, low elevation instrumental measurements would result in a reduced temperature amplitude over the last millennium (Esper et al. 2005).

4.2 Regional-scale comparison

To further assess the reconstructed Alpine JJA temperature history, we compare the new record with regional scale reconstructions by Lamb (1965; Lamb65), Frank and Esper (2005b; Frank 05) and Luterbacher et al. (2004; Luterbacher04) (Fig. 7a). The Lamb65 estimation of June–August temperatures for the European/North Atlantic sector is based on historical evidence. It has a resolution of 50 years making a transformation into temperature anomalies, as done with the other reconstructions, unfeasible. Frank05 used a network of 53 Alpine tree-ring width sites, and applied a nested principal component regression approach to estimate JJA instrumental temperatures. For calibration, homogenized grid data (1×1°) of high elevation monthly mean temperatures over the 1864–1998 period, and for extra verification, low elevation grid data back to 1760 were employed (Böhm et al. 2001). Even though the instrumental data used by Frank05 and this study slightly differ, they correlate with 0.83 and 0.87 over the 1864–1989 and 1760–1863 common periods. Frank05 applied an individual series standardization method, similar to the detrending outlined in the Sect. 2 of this paper, as their network primarily consisted of living tree sites, unsuitable for RCS. The Luterbacher04 multi-proxy reconstruction covers Europe and reaches back to AD 1500. Here we used the updated average of 90 homogeneous grid-points representing the Alpine arc (Casty et al. 2005). For calibration, Luterbacher04 used instrumental data from the Climatic Research Unit (Jones and Moberg 2003; Mitchell et al. 2002; New et al. 2002), which contains characteristic differences in comparison to data released by Böhm et al. (2001). 'The mean annual temperature increase since 1890 in the Alps is 1.1 K, which is twice as much as the 0.55 K in the respective grid boxes of the most frequently used global dataset of the Climatic Research Unit (CRU; Jones et al. 1999)' (Böhm et al. 2001, p. 1779). This dissimilarity originates from differing homogenization procedures applied to the instrumental station records (see Böhm et al. 2001). It is likely that such differences persist back in time, when proxy records—here Luterbacher04 and the current reconstruction—are calibrated to different instrumental target records.

According to the comparison provided in Fig. 7a, the Lamb65 record reveals warm conditions during the putative Medieval Warm Period early in the last millennium, followed by cooler conditions during the Little Ice Age, partly similar to the trends displayed in the new high-resolution Alpine reconstruction. Yet, temperatures during the twelfth and thirteenth centuries in Lamb65 are warmer than in our analysis, where highest temperatures are recorded prior to AD 1000. Note that this early period is influenced by substantial differences between the larch and pine datasets (Sect. 4.1). Also the warm summers during the eighteenth century, reconstructed by Lamb65, are not revealed in this current study.

The Frank05 reconstruction correlates at 0.60 over the past 400 years with the larch/pine composite chronology detailed here. Frank05 is more similar to the long instrumental JJA temperatures over the past 240 years, even though also this reconstruction indicates an offset with the early low elevation instrumental data (Frank and Esper 2005b). The Frank05 reconstruction shows larger inter-decadal variability with little long-term warming over the past 400 years. The higher variability of this record occurs because the mean and variance have been scaled to the instrumental target data, whereas, in the current study linear regression was applied (Esper et al. 2005).

The Luterbacher04 reconstruction correlates at 0.30 and 0.35 after 20-year smoothing (1500–2000) with the new record, and also shows smaller inter-decadal variability with almost no trend over the past 500 years. The substantial trend difference between Luterbacher04 and the current reconstruction might in part be related to the calibration against differing instrumental target records. However, the variance of inter-annual variations, expressed as the amplitude from the coldest to the warmest year over the past 500 years, is quite similar between the two reconstructions, i.e., 4.17°C (1807/1816) for Luterbacher04, and 4.54°C (1821/2001) here. This feature is not visible after smoothing using 20-year low-pass filters, as done in Fig. 7a, as the reconstruction presented here has a much higher lag-1 autocorrelation (0.79) in comparison to Luterbacher04 (0.13), both calculated over the 1500–2000 period of overlap. These features affect the long-term trend behavior and divergence with Luterbacher04.

Overall, the comparison with the regional high-resolution temperature reconstructions reveals similarities in the higher frequency, inter-annual to inter-decadal frequency domain, but indicates substantial differences in the low frequency trends over the past couple of centuries. This discrepancy is related to (1) the use of different (target) instrumental data, (2) differing calibration techniques (scaling and/or regression) including differing calibration periods (3) differing detrending techniques applied to the tree-ring data (RCS or individual standardization), and (4) perhaps slightly differing seasonalities, making an estimation of the long-term absolute temperature amplitude inconclusive.

4.3 Large-scale comparison

A comparison of the new Alpine reconstruction with large-scale temperature reconstructions (Briffa 2000; Esper et al. 2002; Mann et al. 1999) reveals remarkable similarities in the inter-decadal to multi-centennial frequency domains (Fig. 7b). This is despite the fact, that Alpine temperature variations represent only a limited fraction of the temperature fields combined in the large-scale approaches, as well as the seemingly varying datasets, and detrending methods applied in the large-scale records (Cook et al. 2004; Esper et al. 2004).

For 20-year smoothed data (Fig. 7b), the Alpine reconstruction correlates at 0.44 with Esper02, and 0.52 with Briffa00 and Mann99 over the 1000–1980 period of overlap. Key multi-centennial variations common to all records are high values associated with the Medieval Warm Period, a multi-centennial depression corresponding to the Little Ice Age, and a warming trend since about the 1820s (this study, Briffa00, and Esper02). The Mann99 record indicates warming starting around 1900. Whereas, the large-scale reconstructions do not include proxy data during the 1990s, the Alpine reconstruction stretches into the twenty-first century, although the most recent years are less replicated and likely more insecure (Fig. 2).

Maximum similarity between the Alpine and the large-scale reconstructions is seen at decadal scales. All records show low temperatures in the 1350s, 1460s, around 1600, and 1820, and high temperatures in the 1570s, and the 1930s and 1980s. Some of the negative fluctuations are in line with the Little-Ice-Age-Type-Events detailed in Wanner et al. (2000), likely forced by the interaction of volcanic eruptions, i.e., Kuwae (1452), Huaynaputina (1601), and Tambora (1815), and the Wolf (1280–1340), Spörer (1420–1530), Maunder (1650–1710) and Dalton (1795–1825) solar minima (e.g., Briffa et al. 1998; Eddy 1977).

Largest differences occur in the seventeenth and partly the late nineteenth century, although this observation is also affected by substantial differences between the large-scale reconstructions. Generally, discrepancies within the earlier portion of the records are likely affected by decreasing sample size in all records towards the beginning of the past millennium (Esper et al. 2004). The discrepancy around 1700 is most likely related to the Late Maunder Minimum, its spatial characteristics (Camuffo and Enzi 1994; Luterbacher et al. 2001) and seasonal influence on temperatures (Pfister 1999; Wanner et al. 2000). From the 1850s to the mid twentieth century weak coherence between the records exists.

5 Conclusion

A new larch/pine composite chronology is presented, providing evidence of Alpine summer temperature variations back to 951 AD. The record indicates warmer conditions at the beginning of the past millennium, during the putative Medieval Warm Period, followed by an extended period of cooler conditions (the Little Ice Age) and recent warming since about the 1820s. According to this regional analysis, the most recent decade is the warmest period over the past millennium. However, the new Alpine reconstruction is particularly insecure during these recent years—as well as at the beginning of the last millennium—where sample replication is low (e.g., average replication during the 1998–2002 period is 51 larch samples). Long-term, multi-centennial trends and higher-frequency, inter-decadal variations fit quite closely with variations retained in large-scale reconstructions, indicating the relevance of this new record and the Alps to large-scale studies of global climate change. A comparison with other regional temperature reconstructions, nevertheless, demonstrates that the long-term trend and absolute amplitude of temperature variations is not understood. We intend to study this discrepancy more closely by developing well-replicated records of maximum density of both larch and pine species.

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