Improving Alpine summer temperature reconstructions by increasing sample size

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Introduction

Annually resolved reconstructions of multi-centennial to millennial-long temperature variations are commonly derived from tree-ring data (IPCC 2007). A detailed understanding of this proxy archive including growth trends, climate response patterns, eco-physiological disturbances and methodological biases is, however, crucial before robust estimates of past climate variability can be drawn (Esper et al. 2005). Among potential disturbance factors in millennial-length larch (Larix decidua Mill.) chronologies from the European Alps (Büntgen et al. 2005, 2006), effects from periodic oscillations in abundance of the larch budmoth (LBM; Zeiraphera diniana Gn.) are of both concern and interest. LBM is one of the most regular systems of animal population dynamics with a high degree of periodicity in outbreaks every 8-9 years (Baltensweiler & Rubli 1999), and an exceptional persistence over the past millennium (Esper et al. 2007). It is a foliage-feeding Lepidoptera widespread throughout sub-alpine larch forests in the European Alps, and shows considerable variability in temporal population densities ranging from 1 to 30,000 larvae per host tree (Baltensweiler et al. 1977). When such epidemics occur over larger areas, defoliation affects ecosystem processes, but rarely triggers tree mortality. Fingerprints of cyclic LBM outbreaks include significantly reduced larch ring width and density values, that allow long-term LBM dynamics to be estimated, but simultaneously hinder the reconstruction of past climate variations. Since defoliation is not perfectly synchronized over the Alpine arc and along altitudinal gradients (Baltensweiler et al. 2008, Bjørnstad et al. 2002, Johnson et al. 2004, 2006), i.e., there is typically a time-lag of 1-3 years between mass outbreaks, averaging TRW data from different locations could help diminishing the otherwise simultaneous occurrence of severe growth depressions. Scientific importance for such an approach is given, as the retained temperature signal in unaffected larch trees from higher elevations is known to be very pronounced (Frank & Esper 2005), and the longevity of larch timberline trees and the persistence of dry-dead and construction wood has resulted in well replicated composite datasets that are spatially defined and extend back into medieval times (Büntgen et al. 2006a).

Here we present a reconstruction of millennium-long summer temperature variability based on a massive compilation of larch TRW chronologies distributed across the Alpine arc. Calibration/verification trials demonstrate the strength of this unique record to capture the full range of natural temperature fluctuations from inter-annual extremes to lower frequency trends. Wavelet and spectral analyses suggest that increased sample size from a geographically heterogeneous network adequately compensates for non-climatic growth depressions caused by insect defoliation. Effects of changing sample size on the climatic signal strength are discussed in the light of comparison between the new reconstruction and pervious studies based on smaller compilations.

Data and Methods

A compilation of 2610 TRW series from 40 temperature sensitive larch sites located at higher elevations in the European Alps was used for reconstruction purposes (see Büntgen et al. 2008 for details). The Regional Curve Standardization (RCS; Esper et al. 2003) was applied to remove tree...
age related growth trends from the raw measurements allowing lower frequency information to be preserved. Chronologies were calculated using a bi-weight robust mean, and the number of samples per year and the cross-correlation coefficient between all measurements considered for variance stabilization (Frank et al. 2007b). For validation of the overall long-term course of the RCS chronologies, data were split into living (outermost ring >1950), historic (outermost ring <1950), young (<250 years), mature (>150 years), and old (>250 years) trees, according to principles outlined in Büntgen et al. (2005). The six resulting chronologies and their simple mean were compared with instrumental ‘target’ data (Auer et al. 2007). Ordinary linear regression was applied to transfer the dimensionless TRW indices into temperature anomalies with respect to the 20th century mean. The Pearson’s correlation coefficient (r), explained variance (R2), reduction of error (RE), coefficient of efficiency (CE), and Durbin-Watson statistic (DW) were employed to estimate the reconstruction’s skill (Cook et al. 1994). Spectral (Mann & Lees 1996) and wavelet (Torrence & Compo 1998) analyses were applied to perceive similarities and differences in the power spectra of the reconstructed (proxy) and measured (target) time-series.

Figure 1: Temporal distribution of the 2610 living and relict Alpine larch sample used for temperature reconstruction.

Results and Discussion

The Alpine larch TRW dataset is characterized by evenly distributed series start dates from the mid 10th century until the early 20th century (Fig. 1). Mean sample replication during the 951-2004 period is 506 series and ranges from 10-1490. Mean sample replication during the split 951-1477 and 1478-2004 periods are 140 and 872 series, respectively. Minimum and maximum replication during early and late portions are 10 and 391 series, and 44 and 1490 series, respectively. Six RCS chronologies based on the full dataset (2610 series) and subsets of living (1479 series), historic (1131 series), young (1874 series), mature (1593 series) and old (736 series) trees, as well as their arithmetic mean portray common variability on inter-annual to multi-centennial time-scales (Fig. 2). While all records are quite similar back to AD ~1300, increasing offset during the records’ first 350 years most likely originates from constantly decreasing sample sizes back in time. Moving inter-chronology correlations (Rbar) between the six time-series start to slightly decrease before ~1300, whereas moving standard deviations increase during that period (Fig. 2B). A pronounced depression in Rbar values is found around the first half of the 12th century when offset between the individual chronologies is most evident. Nonetheless, one must note that the obtained statistics range on a high level of consistency throughout time. Correlations (common 1122-2003 period) between the six chronologies (after truncation <10 series) range from 0.69-0.97. Values decrease
to 0.46-0.96 after 60-year low-pass filtering. Note that correlation between the fully independent chronologies based on trees younger and older than 250 years is 0.69 (1122-2003). A similar high correlation of 0.63 (1363-1945) derives from the two independent chronologies that either use living or relict wood.

Figure 2: (A) Six chronologies (grey) after various detrendings and their mean (black). The black solid line shows chronology replication ranging from 2-6. (B) Moving 31-year inter-chronologies correlation (Rbar) and standard deviation (STDEV) of the six unfiltered chronologies. (C) Chronologies after 60-year low-pass filtering.

Correlation analysis (1864-2003) between temperatures of an 18-month window from May of the year prior to tree growth until October of the growing season along with various seasonal means and the six RCS chronologies plus their mean reveals a distinct response maximum (r =0.70) to June-July (not sown). Monthly correlations are non-significant from January to May, while correlations with June and July are both significant at p =0.001. Monthly correlations with August to October are again non-significant. After 30-year low-pass filtering, correlations increase to 0.82. Interestingly, correlation coefficients of 0.68 and 0.70 gained from two RCS chronologies using young (<250 years) and old (>250 years) trees, respectively, denote fairly robust growth/climate relationships amongst different age classes. Such age independent signal strength, also demonstrated by Esper et al. (2008), most likely results from the fact that high sample size adequately compensates for juvenile growth ‘disturbances’. In contrast, a more local-scale analysis based on less data, found a maximum climate response in larch trees >200 years (Carrer & Urbinati 2004).
Figure 3: (A) Overlap between the instrumental (grey) and reconstructed (black) temperatures, with the solid line indicating 31-year moving correlations between both records. Temperatures are expressed as anomalies with respect to the 20th century. The grey shading indicates offset between warmer instrumental measurements and cooler proxy estimates. (B) The June-July temperature reconstruction after regressing the mean chronology over the 1864-2003 period. Inset denotes calibration and verification statistics. Series are 20-year low-pass filtered, and grey boxes show the 10 warmest and coldest calendar decades.

After linear regression (1864-2003) of the mean RCS chronology against June-July temperatures (lag-1 autocorrelation of the proxy and target time-series are 0.44 and 0.17, respectively), the reconstruction provides evidence for warmth around the 990s, 1090s and 1170s, a prolonged cooling from the 13th-19th century and exceptionally warm summers since the 1980s (Fig. 3). The warmest and coldest reconstructed calendar decades are the 1990s (+0.88 °C; wrt. 1901-2000) and the 1810s (-2.40 °C), respectively. Warmest summer temperatures back to AD 952 are estimated for 2003 (+2.27 °C) and 983 (+1.69 °C). Seven of the ten warmest summers occurred from 1986 onwards. Positive RE and CE values – estimates of shared variance between actual and reconstructed data – suggest temporal robustness of the model. A DW value of 1.84 (1864-2003) indicates low 1st order autocorrelation in the proxy/target residuals. Temporal stability of the reconstruction is further demonstrated by 31-year moving correlations that describe highest coherency between ~1870-1940 (Fig. 3A). Note that low calibration and verification statistics are obtained during the 1818-1910 period. A similar offset between warmer early instrumental and cooler proxy data is reported from previous Alpine studies and reviewed by Frank et al. (2007a). Comparisons of this reconstruction with two related previous versions of millennium-long summer temperature history from the Alps (Büntgen et al. 2005, 2006b), hereinafter B05 and B06, indicate in-phase variability on all frequency domains (not shown). These reconstructions are, however, not completely independent in terms of the data utilized and methods applied. Correlation (952-2002) between this study and B05 (based on TRW) and B06 (based on MXD) is 0.67 and 0.45, respectively. After 20 (80) year low-pass filtering, correlations with B05 decrease from 0.61 (0.54), whereas correlations with B06 increase to 0.57 (0.57). When splitting the time-series into early (952-1476) and late (1477-2002) portions, correlations with B05 and B06 are 0.61 and 0.29 for the early period and 0.64 and 0.76 for the late period, respectively. After 20 (80) year low-pass filtering,
correlations for the early period decrease to 0.40 (0.15) (B05) and 0.29 (0.17) (B06), whereas correlations for the late period increase to 0.80 (0.83) (B05) and 0.85 (0.90) (B06). Increasing coherency between this study and B05 during the records’ first portion reflects escalating data overlap back in time. High correlations between all time-series during the late period indicate their common signal strength.

We consider the reconstruction back to ~1300 to be an improvement of B05. This is because sample size increased from 1110 larch (and 417 pine) TRW series to now 2610 larch series (it remains debatable if the removal of pine data offsets the augment of larch data) The enhancement is most evident during the records last seven centuries and subsequently helps diminishing LBM-induced ‘noise’ from ~1300-present. Successful compensation for otherwise cyclic growth depressions in TRW results from the heterogeneous dispersal of the 40 site chronologies covering locations from the southern French Pre-Alps to Austria and an altitudinal range from 1400-2200 m asl. This network is characterized by temporal offset in the occurrence of insect outbreaks at different locations.

Both, spectral and wavelet analysis applied to the TRW chronology shows non-significant power at ~8-9 years (Fig. 4), thus not revealing obvious indications of systematic growth periodicities commonly expected at this frequency domain if larch forests are regularly defoliated by LBM outbreaks. Comparison of the power spectra obtained from the proxy and target time-series shows remarkable similarity at all time-scales (Fig. 4A). Significant lower frequency variability of both time-series is indicated at approximately 128, 73 and 44 years. Moreover appears power to be

Figure 4: MTM power spectra of the (A) reconstructed (black) and measured (grey) June-July temperatures (1864-2003) using 3 tapers and a resolution of two years with robust background noise estimation. Smoothed lines are 95% confidence limits. The upper right inset denotes the corresponding global wavelet power spectra, with the dashed lines being 90% significance levels. (B) Global wavelet power spectra of the TRW-based reconstruction computed over two early/late split periods. Dashed lines are 90% significance levels using a white noise background.
significant at the inter-annual time-scale. Artificial power inflation as obtained from the target time-series towards lowest frequencies most likely reflects the overall long-term warming from the mid-19th century until 2003, rather than really fluctuations. Negligible power between 7-10 years, caused by the geographically random merging of TRW data from numerous larch sites, contrasts results obtained from the site-level (see Esper et al. 2007 for details). At the local-scale, TRW chronologies have in fact demonstrated the detection of LBM defoliation-induced growth reductions near Italian/French border (Nola et al. 2006), across two sub-alpine valleys in Switzerland (Weber 1997), and within the French Alps (Rolland et al. 2001). These recent studies conducted at the local-scale, nicely confirmed the regular recurrence of outbreaks with little evidence for changes in cycle period and amplitude over the last few centuries prior to the widespread collection of forest inventories data. Outstanding in this regard appears the 1200-year long history of insect epidemics developed on the basis of a sub-alpine TRW/MXD hybrid from living trees and historic timbers (Esper et al. 2007).

For a better understanding of the fidelity to diminish cyclic growth depressions at ~8-9 years back into medieval times when series sample size and spatial heterogeneity of the sites constantly decreases – most of the site chronologies that stretch well into the records first half are located in the western Swiss Alps, wavelet analysis was applied over two split periods (951-1477 and 1478-2004) of equal length (Fig. 4B). To pinpoint inter-annual to decadal-scale power peaks, the wavelet significance levels are based on a white noise background spectrum (Torrence & Compo 1998). While significant power associated with LBM outbreaks is found during the first interval, no such evidence derives from the second interval. This difference in the reconstructed strength of cyclic growth depressions during the early and late portion of the record is related to (i) the enormous difference in sample size, and (ii) the spatial network change from the regional- to larger-scale, as long-term consistency in LBM system itself has been proofed (Esper et al. 2007). While a mean replication of 140 series versus 872 series before and after AD 1477 already obscures compensating defoliation-induced growth depressions by high sample size alone, most of the site chronologies that extend back into medieval times derive from the same region in the western Swiss Alps.

**Conclusion**

A compilation of 2610 TRW series from 40 sites covers the Alpine arc and the 951-2004 period. Application of the RCS method resulted in a chronology that preserves inter-annual to multi-decadal scale variability. Since sample size and diversity in sample compensates for spatiotemporally asynchronous insect-induced ‘noise’, reconstructed summer temperatures show, for example, the cold and hot extremes of 1816 and 2003, respectively, as well as episodic warming during medieval times and towards present with prolonged Little Ice Age cooling in between.

This reconstruction validates earlier work and also improves our understanding of past climate variability across the Greater Alpine Region and back in time. This study exhibits that larch TRW measurements can robustly model summer temperature variations if enough data (i.e. evenly distributed and well replicated site chronologies) are carefully selected (i.e. based on their individual temperature response) and age-related composite detrending properly applied (i.e. tests of the RCS method using various data subsets).

Conversely, this study supports the ‘epicenter’ hypothesis of traveling waves in population dynamics (Johnson et al. 2004), and the ‘altitude’ hypothesis, which postulates that most severe LBM epidemics are concentrated at ~1800 m asl (Weber 1997). While the first hypothesis is affected by the complex landscape geometry of the Alpine arc that dampens the direction and speed of traveling waves (Bjørnstad et al. 2002, Johnson et al. 2006), the later is affected by local weather conditions that shift outbreak foci to lower or higher elevations, and modulate populations at different slope exposures (Baltensweiler et al. 2008).
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References


