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A 500 YEAR DENDROCLIMATIC RECONSTRUCTION OF SPRING–SUMMER PRECIPITATION FROM THE LOWER BAVARIAN FOREST REGION, GERMANY

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ABSTRACT

This paper presents a 500 year March–August precipitation reconstruction for the Bavarian Forest region of southeast Germany based on a composite, well-replicated data set of 676 living and historical tree-ring width series from Norway spruce. Two versions of the chronology are developed. The cubic smoothing spline (SPL) chronology, standardized with a fixed 80 year spline function, retains decadal and higher frequency variation. The regional curve standardization (RCS) chronology uses regional curve standardization to retain additional lower frequency variation from the same data. Calibration (1879–1978) of these chronologies with March–August precipitation indicates they explain 40% (SPL) and 34% (RCS) of the variability in the instrumental precipitation record. The SPL reconstruction models the high-frequency variation better, whereas the RCS reconstruction tracks the low-frequency trends more robustly. It suggests that spring–summer precipitation was above the long-term average for the periods 1730–1810 and 1870–2000, about average between 1560 and 1610 and that significantly drier periods occurred during 1510–60, 1610–35, 1660–1730 and 1830–70. The low-frequency trends of the RCS reconstruction during the 19th century were verified by comparison with a regional precipitation series derived from 14 long precipitation records from central Europe. Better verification results were obtained using the original (non-homogenized) records over this interval. These results suggest that some low-frequency variability may have been removed during correction of these early records. Periods of synchronous decadal variability were observed between the SPL series and independent dendroclimatic reconstructions from central Europe. The RCS reconstruction is the first dendroclimatic precipitation reconstruction in Europe to capture low-frequency information. These long-term trends, however, are difficult to verify owing to the paucity of other proxy precipitation records in central Europe that portray low-frequency information. Further verification and testing of the RCS reconstruction will require the development of additional reconstructions from tree-rings (or other proxy data series) that similarly target low-frequency variability. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: dendroclimatology; ring width; precipitation; reconstruction; low frequency; Bavarian Forest; Germany

1. INTRODUCTION

Long, annually resolved tree-ring (TR) records have been used to estimate changes in precipitation variability over several centuries in many regions of the world (e.g. D'Arrigo and Jacoby, 1991; Stahle and Cleaveland, 1992; Lara *et al*., 2001; Pederson *et al*., 2001; Watson and Luckman, 2001; Brázdil *et al*., 2002). Such records provide benchmarks that place recent climate changes in a long-term context (Briffa, 2000). Most reconstructions of precipitation or related parameters (e.g. stream flow and aridity indices) are from North America, where drought is common and the quality and quantity of available water is a critical control of many economic activities (Cook *et al*., 1999). In central Europe, drought is generally not a major influence on

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economic stability and there have been few attempts to reconstruct changes in past precipitation. However, the record-breaking central European floods in 2002 (Vogel, 2002; Ulbrich *et al*., 2003a,b) and the widespread European drought in 2003 demonstrate the need for a better understanding of precipitation variability in this region.

Although early dendrochronological studies indicated that the growth of low-elevation conifers in central Europe can be limited by moisture availability (von Jazewitsch, 1961; Becker, 1978), few attempts have been made to reconstruct precipitation from TR series (Brázdil *et al*., 2002; Oberhuber and Kofler, 2002). Until recently, documentary sources have provided the primary archives for information on past precipitation variability (Brázdil, 1992, 1996; Pfister, 1992, 1995, 1999; Glaser, 1998, 2001). Although central Europe lacks semi-arid environments, dendrochronological studies have shown that a statistically robust precipitation signal can be identified in some low elevation conifer tree species (von Jazewitsch, 1961; Becker, 1978; Dittmar and Elling, 1999; Wilson and Hopfmueller, 2001; Brázdil *et al*., 2002; Oberhuber 2002; Wilson and Elling, 2004). The development of TR proxies of past precipitation would, therefore, be an invaluable contribution to increasing the understanding of recent changes in precipitation in the region.

This paper presents a 500 year dendroclimatic reconstruction of spring–summer precipitation for the lower Bavarian Forest region of Germany, using a composite ring-width (RW) chronology developed from living Norway spruce (*Picea abies* (L.) Karst) and historical timbers. It is the first long dendroclimatic precipitation reconstruction for central Europe that expresses centennial-scale climatic information.

2. DATA SOURCES

2.1. Developing a regional precipitation series for the Bavarian Forest (BF_{ppt})

Precipitation data from 14 meteorological stations in the Bavarian Forest region (Figure 1, Table I) were selected to develop a regional precipitation series for calibration purposes. The data were provided by the German Weather Service and have been corrected (Herzog and Müller-Westermeier, 1998) and verified for

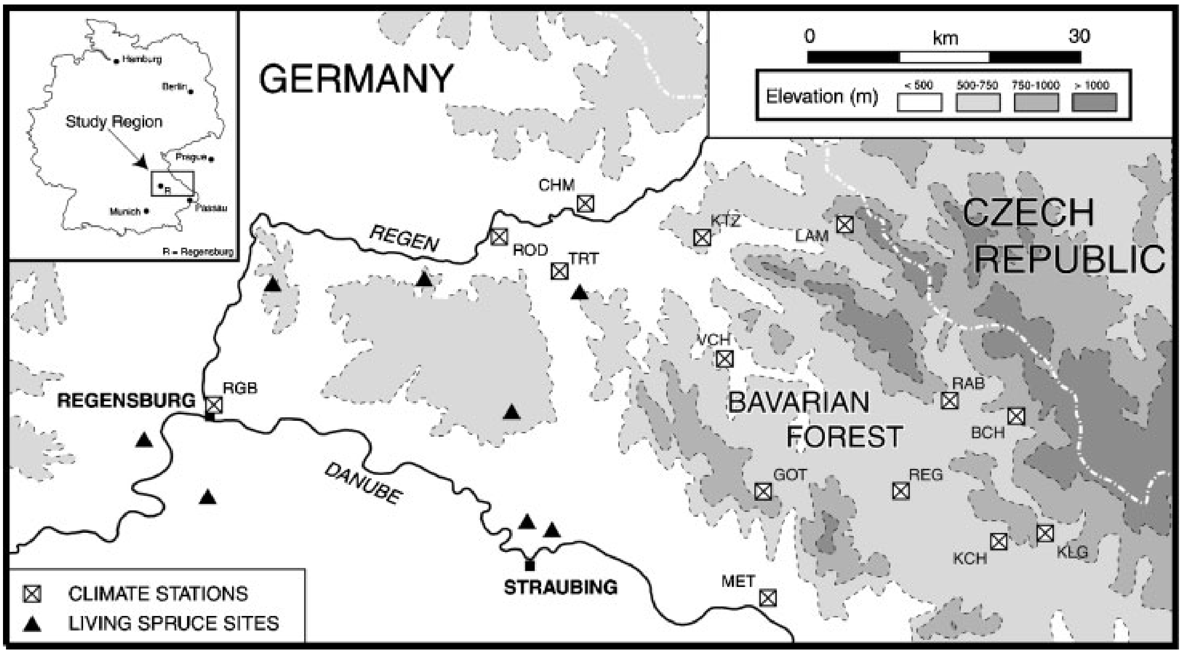

Figure 1. Location map of the TR chronology sites and meteorological stations (see Table I for station codes) in the Bavarian Forest region. Historical TR samples were taken from buildings in or around Regensburg and Straubing. The low-elevation living spruce chronologies were sampled from the probable source region for the timbers used in construction (see Wilson *et al*. (2004))

Table I. Precipitation records used from the Bavarian Forest region. MEAN: mean annual (January–December) total precipitation over period 1913–95. The PC loadings were obtained from a PCA analysis of March–August precipitation between the stations over the 1913–95 period using both correlation (CRM) and covariance (CVM) matrices

Station code	Meteorological station	Elevation (m)	Record length	MEAN (mm)	PC Loadings	
					CRM	CVM
KLG	Klingenbrunn	823	1911–2001	1177	0.88	0.91
BCH	Buchenau	740	1891–2001	1329	0.86	0.88
KCH	Kirchdorf	693	1899–1999	1027	0.89	0.90
RAB	Rabenstein	690	1881–2001	1294	0.89	0.92
GOT	Gotteszell	576	1913–2001	1136	0.87	0.87
REG	Regen	572	1899–2001	949	0.88	0.88
LAM	Lam	541	1901–2000	1038	0.81	0.81
VCH	Viechtach	455	1901–2001	859	0.89	0.88
TRT	Traitsching	435	1900–1995	764	0.86	0.84
KTZ	Kotzting	408	1901–2001	839	0.93	0.91
CHM	Cham	396	1879–2001	705	0.82	0.79
RGB	Regensburg	366	1871–2001	636	0.76	0.72
ROD	Roding	363	1895–2001	705	0.88	0.85
MET	Metten	313	1879–2001	943	0.90	0.90

homogeneity problems (verification was carried out using double mass plots (Kohler, 1949) of cumulative precipitation between pairs of stations for each of the seasons (Wilson, 2003)). Principal component analysis (PCA; Richman, 1986; Baeriswyl and Rebetez, 1997) was used to assess the common signal between the 14 precipitation records over the 1913–95 period. Despite mean seasonal precipitation totals increasing with elevation (Table I), only one significant eigenvector was identified using correlation and covariance matrices for each of the four seasons (Wilson, 2003). It should also be noted that the mean elevation of the 14 meteorological stations is *ca* 500 m and that 12 of these stations are within the low-elevation zone (<700 m; Wilson *et al*., 2004) from which the TR chronologies were sampled. The PCA results, therefore, indicate that the year-to-year variability is spatially homogeneous within the region; therefore, the data from the 14 stations were averaged, using techniques outlined in Jones and Hulme (1996), to develop a mean regional series. Monthly values for each station were standardized as z-scores relative to the 1913–95 common period and averaged to calculate monthly z-scores for the regional average series. These monthly z-scores were converted to 'absolute' precipitation values using the average of the means (grand mean) and standard deviations (grand standard deviation) of each of the original monthly series. The complete Bavarian Forest regional precipitation (BF_{ppt}) record extends from 1871 to 2001 (Table I).

The expressed population statistic (EPS; Wigley *et al*., 1984; Briffa and Jones, 1990) was used to assess the theoretical number of climate series needed to acquire a robust mean function that represents the 'true' population signal. The mean between series correlation using the maximum overlap of all 14 records for each of the monthly series is 0.82, indicating a strong common signal between the precipitation records. The theoretical estimated minimum number of time series n needed to obtain an EPS of a particular value was calculated using

$$n = \frac{(\overline{r} - 1)\mathrm{EPS}(x)}{\overline{r}(\mathrm{EPS}(x) - 1)} \tag{1}$$

where the threshold value of EPS(x) is user defined and $\overline{r}$ is the mean between series correlation. An EPS value of 0.85 was suggested by Wigley *et al*. (1984) as a reasonable threshold for signal acceptance. Using this threshold, the estimated mean minimum number of climate series needed to develop a regionally representative series is 1.2. However, the 1871–78 period was eliminated from the regional record as it is only represented by a single station (Regensburg) and only the 1879–2001 interval was considered for calibration purposes. It should also be noted that Regensburg has the weakest loadings in the PCA (Table I) and, therefore, does not contain the strongest regional signal. Nevertheless, it is important to include it in the regional record because of its proximity to the sampling region.

2.2. *Developing long precipitation series for central Europe (CE_{ppt} and CEU_{ppt})*

Data from 14 long meteorological records from areas adjacent to the study region (Figure 2) were utilized to provide independent validation of the low-frequency trends in the precipitation reconstructions for the Bavarian Forest region prior to 1879. Both corrected and non-corrected monthly precipitation data are available for 13 of the 14 stations selected. Documentation of the acquisition and correction techniques used for the early 19th century data is poor and uncertainties remain about the quality of some early records (even where they have been corrected: Beck, personal communication 2002; see Beck (2000) and Auer *et al*. (2001)). Therefore, two regional precipitation series were developed based exclusively on the homogenized (CE_{ppt}) or uncorrected (CEU_{ppt}) data.

The correlation between the instrumental March–August precipitation series for BF_{ppt} (used for calibrating the TR data) and homogenized data from each of these 14 long records over the 1879–1978 interval is variable, ranging from 0.29 (Vienna) to 0.77 (Augsburg, Figure 2). Although there is some spatial heterogeneity (the more distant station data correlate more weakly), the high correlations with the majority of the proximal sites

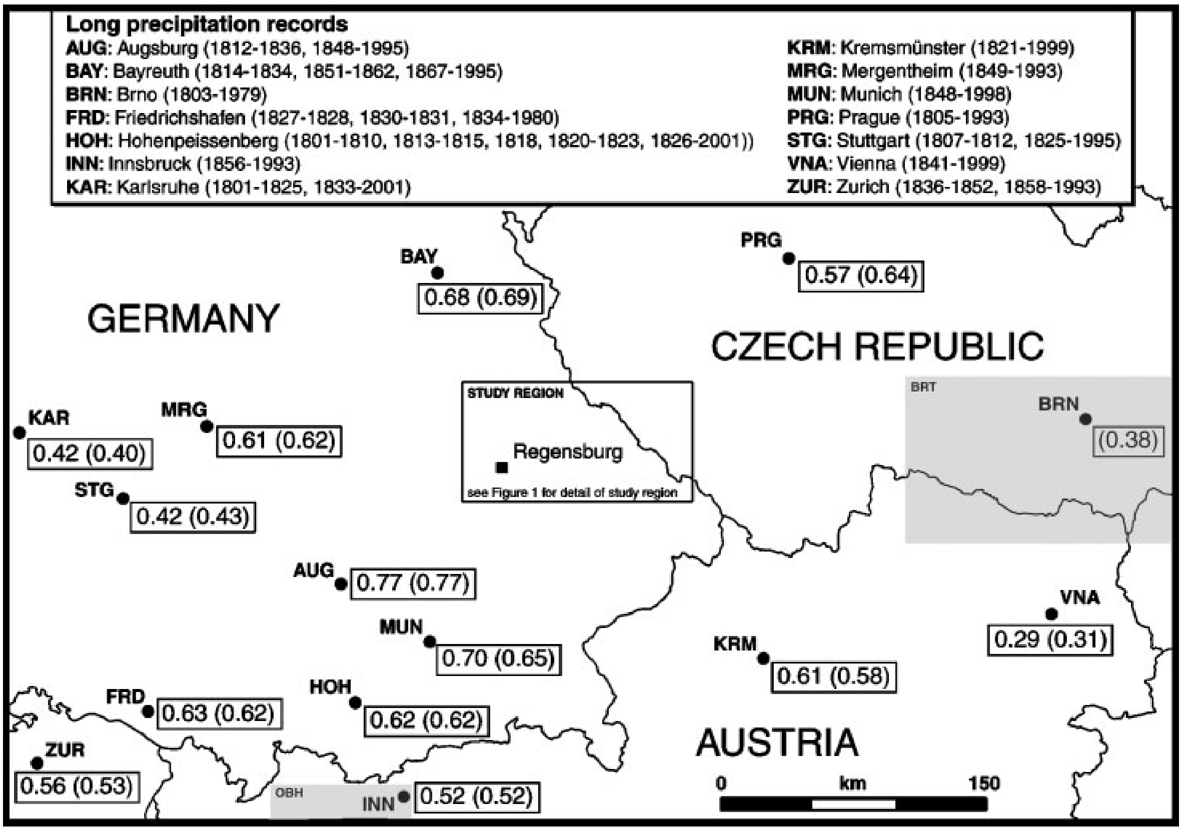

Figure 2. Location of the 14 long precipitation records used to assess the trends in the RCS reconstruction in the 19th century (Figure 8, below). The station name and available March–August precipitation data are listed in the inset box. The boxed values denote the correlation between the Bavarian Forest precipitation series (BF_{ppt}) and the homogenized and/or uncorrected records (in parentheses) for each station for the March–August period between 1879 and 1978. All correlations are significant at the 95% confidence level. The light-grey boxes denote the regions from where TR samples were taken for the Brázdil *et al*. (2002) and Oberhuber and Kofler (2002) TR reconstructions, BRT and OBH respectively (see Table IV)

indicate that precipitation patterns in BF_{ppt} are coherent with a large part of central Europe. Therefore, a regional series, combining all 14 long records, should provide an independent data set against which to test the quality of the precipitation reconstructions, particularly for the period before 1879 when no Bavarian Forest precipitation data are available. The two long central European series (CE_{ppt} and CEU_{ppt}) were developed separately using the same Jones and Hulme (1996) procedures outlined above for the BF_{ppt} series and normalized relative to the 1879–1978 period. (Each series was normalized prior to averaging and again after averaging because the variance of the mean series was reduced through the initial averaging process. The 1879–1978 period is used for calibration.) The correlations of CE_{ppt} and CEU_{ppt} with BF_{ppt} over the 1879–1978 interval are 0.82 and 0.81 respectively for the March–August season.

2.3. *The Bavarian Forest TR data*

Dendroclimatology is possible when growth at a TR site is primarily limited by a single climatic factor (Fritts, 1976), allowing variation in the RW characteristics to be interpreted in terms of that factor (e.g. precipitation). Historical TR material has rarely been used in dendroclimatic reconstructions (Schweingruber *et al*., 1988; Richter and Eckstein, 1990; D'Arrigo and Jacoby, 1991; Brázdil *et al*., 2002; St George and Nielsen, 2002; Wilson and Topham, 2004) because the precise growth site of the original wood is generally unknown; it cannot, therefore, be assumed that the historical and living TR series contain similar climatic information. In this study, TR chronologies were developed from living trees and from beams preserved in historical buildings in the lower Bavarian Forest region of southeast Germany (Figure 1). The buildings sampled were restricted to a relatively small area where the construction timbers used were thought to be of local origin. Low-elevation (< 700 m) living-tree chronologies (Wilson and Hopfmueller, 2001) provided reference material against which to cross-date the historical timbers. Wilson *et al.* (2004) compared the statistical properties of these RW series and demonstrated that the historical timbers used in this region were from trees growing at local, low-elevation sites. As RW series from low-elevation spruce stands of this region are strongly correlated with spring–summer precipitation (Dittmar and Elling, 1999; Wilson and Hopfmueller, 2001; Wilson and Elling, 2004), RW series from the historical materials should contain the same environmental signal. Therefore, these historical TR data are suited both to extending the chronology from low-elevation living TR series and to developing precipitation reconstructions. The living tree and historical chronologies were therefore composited into a single Norway spruce chronology covering the period 1456–2001 (Wilson, 2003).

3. TREE RING CHRONOLOGY DEVELOPMENT

RW series often show a non-climatic, age-related trend that must be removed prior to chronology development and dendroclimatic analyses (Fritts, 1976). As traditional detrending methods do not distinguish between biologically and climatically controlled trends, this process may remove low-frequency climate signals on time scales that roughly equate to the mean length of the samples (segments). This problem is known as the 'segment length curse' (Cook *et al*., 1995).

The spruce composite chronology for the Bavarian Forest region consists of 676 radii from eight living and 40 historic TR chronologies with an overall mean sample length (MSL) of 81.2 years. Ignoring the poorly replicated pre-1500 period, the lowest MSL is between 70 and 80 years over the 1650–1700 interval (Figure 3). Cook *et al*. (1995) state that the lowest frequency of climate information that can be realistically recovered from traditionally standardized series is $3/n$ cycles per year (where n is the MSL). This severely limits the reconstruction of low-frequency trends, as only decadal-scale variability could be retrieved from records with an MSL of *ca* 80 years. Moreover, because MSL varies throughout this spruce chronology (Figure 3), traditional detrending methods would result in a composite series with a variable low-frequency signal over time.

Two standardization strategies are employed to address these limitations. The spline (SPL) chronology was developed by detrending all RW series individually with a fixed 80 year spline (Cook and Peters, 1981). This

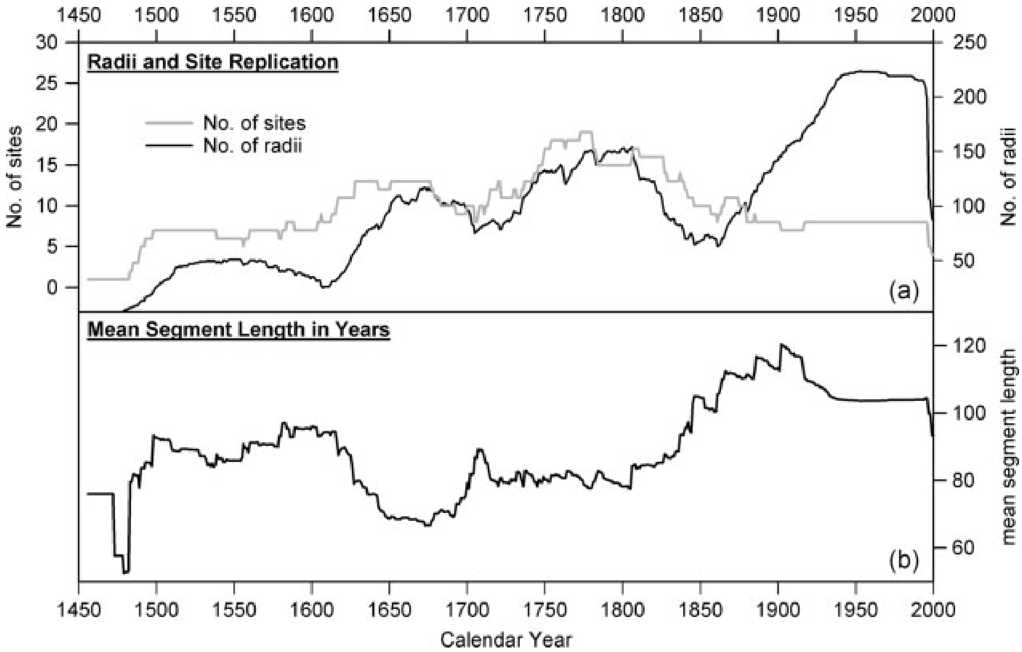

Figure 3. Replication of radii, number of sites and MSL data for the spruce living/historic TR series

approach represents the amount of lower frequency information, using traditional single-series detrending methods, that would be captured from data with an MSL of *ca* 80 years and captures only decadal and higher frequency variability in the TR chronology. A second chronology was developed using the regional curve standardization (RCS) method (Mitchell, 1967; Cook *et al*., 1995; Briffa *et al*., 1996; Esper *et al*., 2003) that aims to capture secular-scale variability at frequencies greater than the MSL (see Appendix A for details).

The variance of the raw RW series was stabilized using an adaptive power transform procedure (Cook and Peters, 1997) and the modelled age trends were removed by subtraction in both chronologies. As there was marked variation in the number of samples in the individual historic and living chronologies, each composite chronology was developed by averaging the site chronologies to reduce this sampling bias (see Appendix A). The variance of the site and final composite chronologies were temporally stabilized using techniques outlined in Osborn *et al*. (1997).

The SPL chronology retains adequate signal strength (EPS > 0.85) back to *ca* 1500 (Figure 4), whereas the RCS series has weaker signal strength prior to *ca* 1600 and around the period of overlap (1850–1900). This slightly weaker signal strength is related to the nature of the RCS method compared with standard detrending approaches. However, the RCS chronology clearly shows more low-frequency information and indicates that 20th century index values are generally higher than at any other period in the previous 400 years. The extended periods of low index values that occur, *ca* 1510–60, 1610–1725 and 1825–75, cannot be identified in the SPL chronology (though several individual decades of low index values occur throughout the record). The different standardization methods have, therefore, produced radically different time series from the same input data. These differences in the frequency domain must be recognized when comparing these data with other series.

4. DENDROCLIMATIC RECONSTRUCTION

4.1. Calibration trials

Wilson and Hopfmueller (2001) demonstrated that the dominant climate signal in the TR series from low-elevation spruce in this region was a positive response with spring–summer precipitation. Calibration trials were undertaken using both chronologies to identify the optimal season for reconstruction. Each of

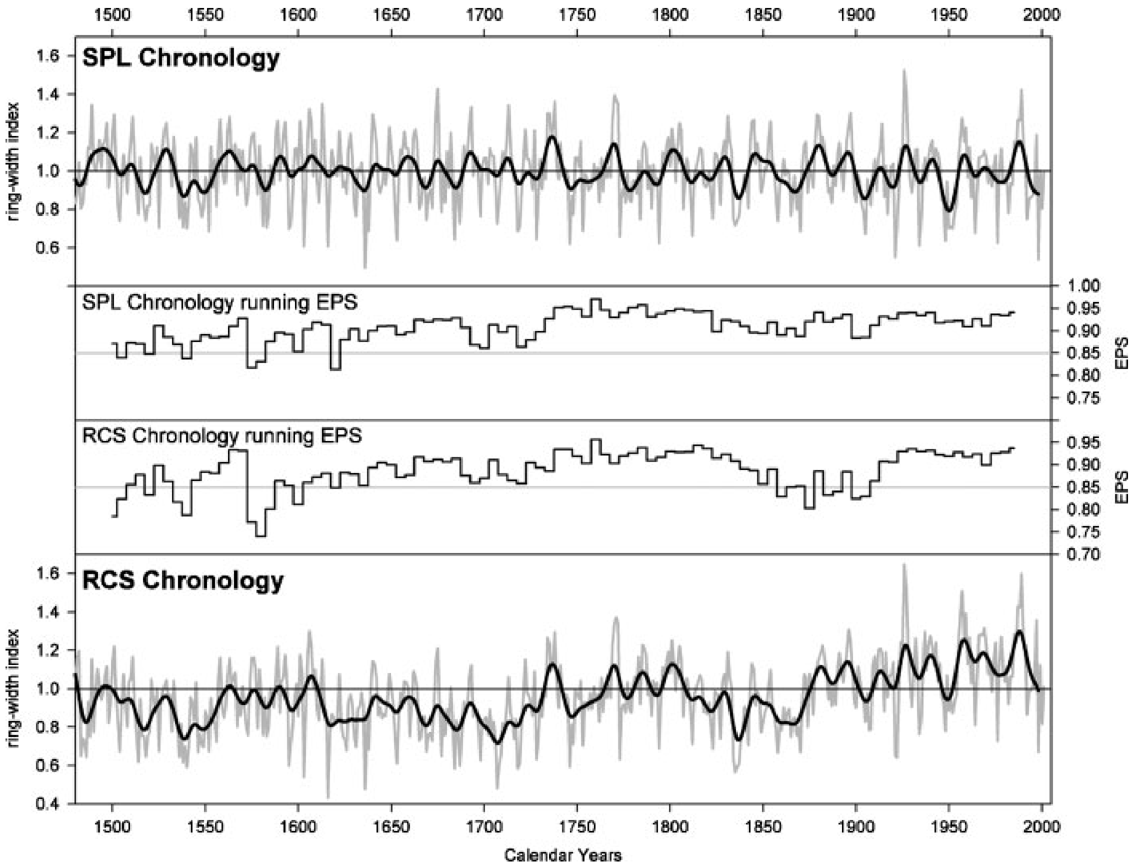

Figure 4. Comparison between the SPL and RCS living/historic composite chronologies. The bold curve is a 15 year smoothing spline (Cook and Peters, 1981). Running 30 year (lagged by 5 years) EPS plots are shown for each chronology to indicate the signal strength of these chronologies. The EPS is a quantitative measure of how a 'sample' of RW series, when averaged together, portray a hypothetical perfect 'population' chronology. A value of 0.85 (grey horizontal line) is generally considered adequate for dendroclimatic purposes (Wigley *et al.*, 1984; Briffa and Jones, 1990)

the chronologies was lagged at $t-1$, t, and $t+1$ to ensure that the effects of the previous year's climate upon growth were included in the modelling. Using stepwise linear regression, the lagged variables for each chronology were regressed against differing seasons of precipitation over the period 1879–1978 (Figure 5). Calibration trials excluded data after 1978, as Wilson and Elling (2004) showed a significant weakening in the climate signal in low-elevation spruce sites over the last two decades, probably due to SO_2 emissions from nearby refineries and power stations.

The SPL series accounts for more of the climate variance than the RCS chronology for all the seasonalized precipitation series over the current growth year (Figure 5). This is not unexpected, as the SPL series has greater signal strength (Figure 4) and similar observations have been made in other comparisons of 'traditional' and RCS standardized chronologies (Briffa *et al.*, 1992; Cook *et al.*, 2003). The strongest signal is with spring–summer precipitation, and March–July precipitation shows the highest value for both chronologies (Figure 5). However, although calibration trials for the March–July and March–August periods show that modelled variance using March–July precipitation is almost always stronger (Table II), there is a marked weakening in the March–July signal for the 1929–78 period. This time instability in the tree-growth/climate signal is particularly marked using the RCS chronology, where only 19% of the March–July precipitation variance is explained for the later period. Brázdil *et al.* (2002) describe a similar loss of climate signal after 1956 in their calibration of a March–July precipitation reconstruction from a fir chronology in the Czech Republic (see BRT, Figure 2).

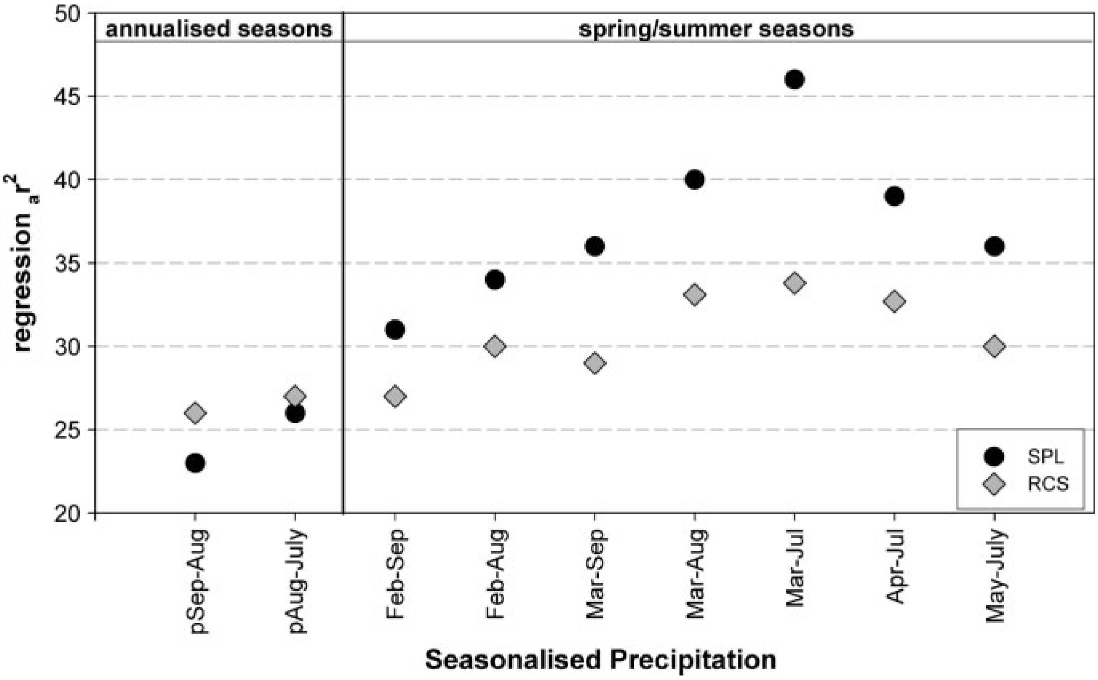

Figure 5. Calibration trial results (utilising all lagged ($t-1$, t, and $t+1$) variables) comparing the SPL and RCS chronologies against selected seasonal precipitation totals. All adjusted r^2 values are significant at the 95% confidence level

Table II. Split period calibration trial results (adjusted r^2) for both the SPL and RCS reconstructions against March–July and March–August precipitation. For each period, lagged variables ($t-1$, t, and $t+1$) were regressed, using a stepwise procedure, against each season over the periods 1879–1928 and 1929–78

	SPL reconstruction		RCS reconstruction	
	1879–1928	1929–78	1879–1928	1929–78
March–July	63%	37%	45%	19%
March–August	49%	34%	35%	34%

As the calibration period has already been truncated at 1978 due to recent effects of SO_2 emissions upon spruce growth (Wilson and Elling, 2004), further shortening of the calibration period would make it difficult to explain the differences in low-frequency trends between the SPL and RCS chronologies (Figure 4). Therefore, we model the more time-stable March–August relationship rather than a March–July period that explains more variance but would be restricted to a smaller calibration window. This compromise model explains a reasonable amount of climatic variance for both series with adequate signal fidelity through the calibration period and maximizes the length of the calibration period to improve the assessment of low-frequency trends in the original chronologies.

4.2. Calibration and verification

Separate reconstructions of March–August precipitation totals were developed from the SPL and RCS chronologies using multiple linear regression. The predictor chronologies were lagged at $t-1$, t, and $t+1$ to ensure that the effects of previous years' climate upon growth were included in the modelling. The lagged series were entered into the regression using a stepwise procedure (F-to-enter $= 0.05$; F-to-remove $= 0.10$)

to minimize multicollinearity in the models. Multicollinearity in the final models was assessed using the determinant of the correlation matrix of the predictor variables (McCuen, 1985). Full model calibration was made over the period 1879–1978, and split period calibration/verification (1879–1928 and 1929–78) was undertaken to assess the temporal stability of the identified models. The verification statistics used were Pearson's correlation coefficient r, the reduction of error (RE) statistic, the coefficient of efficiency (CE) and the sign test (Fritts, 1976; Cook *et al*., 1994).

The final reconstructions explain 40% (SPL) and 34% (RCS) of the precipitation variability and both models pass all verification statistics (Table III). The matrix determinants for both regression models exceed 0.5 (Table III), indicating that there is no significant multicollinearity in either model and that the explained variance is not inflated due to 'artificial predictability' (Cook *et al*., 1994). The actual and predicted series show a linear relationship, and both reconstructions model the high- and low-frequency variation reasonably well (Figure 5(a) and (b)). However, although the residuals from both models show no significant autocorrelation at the 99% confidence level (Figure 6(c)), the residual series for the SPL reconstruction does show a significant linear increase in values that suggests the SPL reconstruction may not model longer term variation as well as the RCS series. This observation is confirmed by the stronger correlation between actual and predicted smoothed series for RCS over the calibration period (Figure 6(d)).

The results presented in Table III and Figure 6 indicate that both models are valid, robust dendroclimatic reconstructions of past March–August precipitation variability for the region. However, the SPL reconstruction is slightly better at modelling the higher frequencies, whereas the RCS reconstruction appears to model lower frequency variation more robustly.

The RCS reconstruction shows more low-frequency variability (Figure 7) and suggests that spring–summer conditions were wetter than the long-term average over the periods 1730–1810 and 1870–2000, with the 1560–1610 period showing precipitation levels roughly equal to the long-term average. Dry periods are identified for 1510–60, 1610–35, 1660–1730 and 1830–70. All of these reconstructed drier periods predate the Bavarian Forest instrumental record and cannot be verified directly. Therefore, this earlier part of the reconstruction is assessed by comparison with long climate records and other proxies of spring–summer precipitation from central Europe.

Table III. Calibration and verification statistics for March–August precipitation reconstructions[a]

Calibration					Verification				
Period	r	r^2	aR^2	SE	Period	r	RE	CE	ST
SPL									
1879–1928	0.72	0.52	0.49	73.5	1929–78	0.55	0.18	0.16	38/12
1929–78	0.62	0.38	0.34	75.2	1879–1928	0.66	0.37	0.36	41/9
1879–1978	0.64	0.41	0.40	75.8	MD = 0.55				
$\text{Prec}_{(\text{March–August})} = 275.8 + 339.8\text{TRW}_t - 214.3\text{TRW}_{t+1} + 109.6\text{TRW}_{t-1}$									
RCS									
1879–1928	0.62	0.38	0.34	83.4	1929–78	0.52	0.25	0.23	36/14
1929–78	0.62	0.39	0.35	74.8	1879–1928	0.53	0.29	0.28	35/15
1879–1978	0.60	0.36	0.34	79.5	MD = 0.58				
$\text{Prec}_{(\text{March–August})} = 229.9 + 302.3\text{TRW}_t - 147.4\text{TRW}_{t+1} + 100.9\text{TRW}_{t-1}$									

[a] r: correlation coefficient; r^2: explained variance; aR^2: square of the multiple correlation coefficient following adjustment for loss of degrees of freedom; SE: standard error of the estimate; RE: reduction of error statistic; CE: coefficient of efficiency statistic. Both RE and CE are measures of shared variance between the actual and modelled series, but are usually lower than the calibration r^2. A positive value for either statistic signifies that the regression model has some skill. CE is the more rigorous statistic. (Cook *et al*., 1994). ST: sign test (Fritts, 1976); MD: matrix determinant. If this is >0.5, the regression model has no significant multicollinearity (McCuen, 1985).

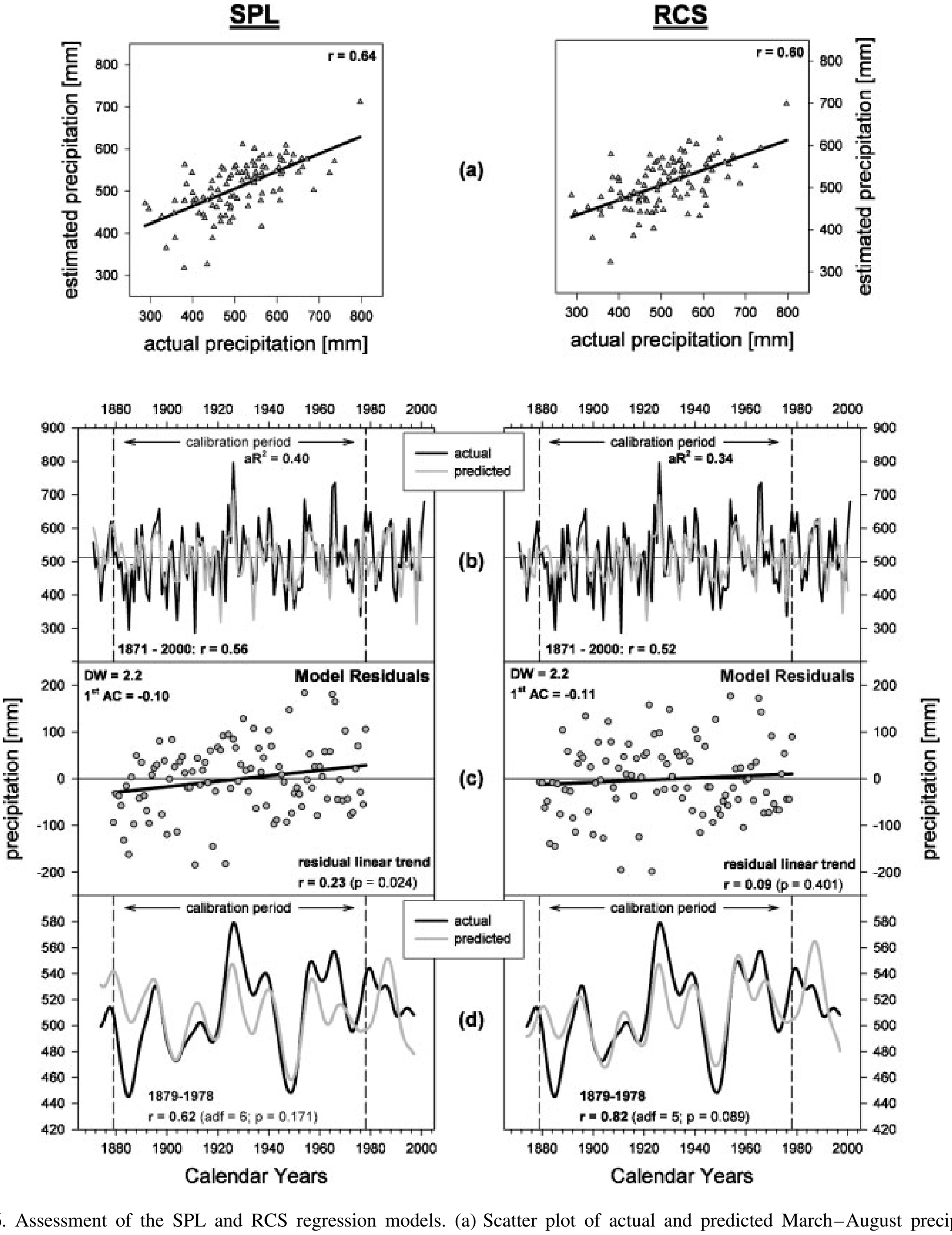

Figure 6. Assessment of the SPL and RCS regression models. (a) Scatter plot of actual and predicted March–August precipitation totals with linear relationship highlighted. (b) Comparison of actual and predicted March–August precipitation totals (1871–2000). The 1879–1978 calibration aR^2 and full-period (1871–2000) correlation (significant at the 95% confidence level) are shown. (c) Scatter plots of model residuals (1879–1978). The Durbin Watson (DW) statistic and first-order autocorrelation (AC) values show that the residuals show no significant autocorrelation at the 99% confidence level. The linear trend of the residuals is also shown and the significance of the trend is shown in the bottom right-hand corner of each graph. (d) Comparison of low-pass-filtered series (15 year cubic smoothing spline) of the actual and predicted precipitation series. adf: adjusted degrees of freedom. The degrees of freedom were adjusted to account for the autocorrelation in the smoothed series so that significance of the correlations could be assessed (Pyper and Peterman, 1998)

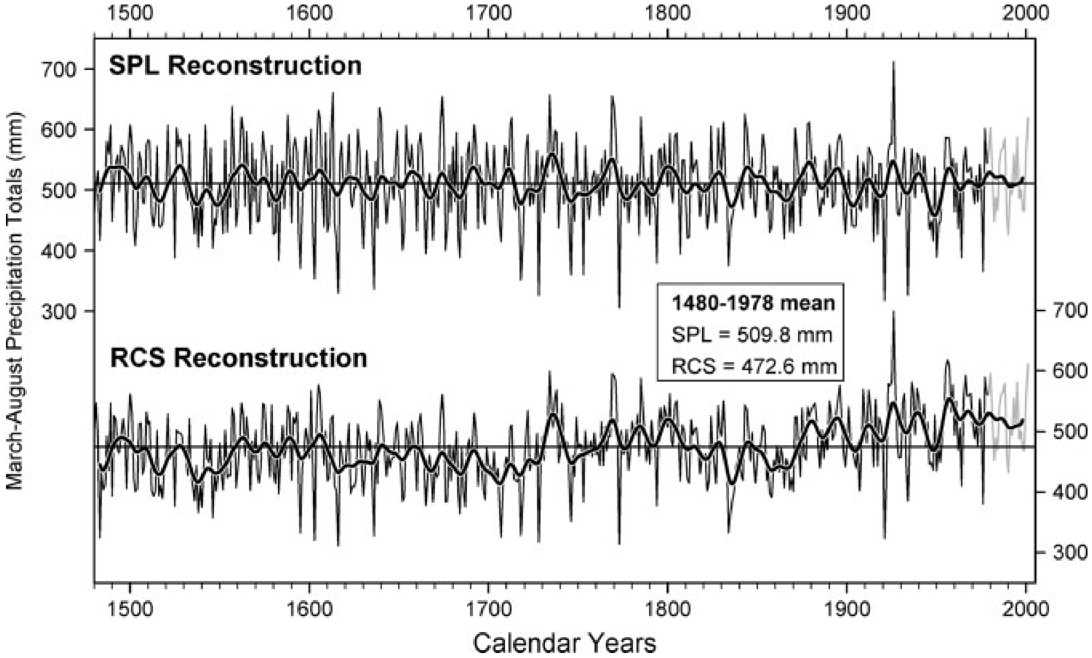

Figure 7. Time series plot of the SPL and RCS reconstructions, 1480–1978. The post-1978 series is represented by actual March–August precipitation (grey) after they had been scaled to the mean and standard deviation of the respective reconstructions over the 1878–1978 period. The black smoothed line is a 15 year cubic smoothing spline (Cook and Peters, 1981)

5. INDEPENDENT ASSESSMENT OF THE SPL AND RCS RECONSTRUCTIONS

5.1. Comparison with long meteorological records over the last two centuries

Comparison of the decadal trends of the RCS reconstruction with both central European precipitation series (CE_{ppt} and CEU_{ppt}) shows substantial agreement over the 1879–1978 calibration period (Figure 8). This similarity indicates that, despite being derived from a relatively small area, the RCS reconstruction covaries with, and is therefore representative of, precipitation over a much larger area in central Europe. However, this coherence breaks down after *ca* 1980 (see also Figure 6), supporting Wilson and Elling's (2004) observation that the growth/climate response of low-elevation spruce trees in the Bavarian Forest region weakened after the late 1970s. The reconstructed values for the last few decades should, therefore, be interpreted with caution.

Prior to 1879, the low-frequency trends in the RCS reconstruction more closely follow the 'uncorrected' (CEU_{ppt}) instrumental data (Figure 8(b)), differing significantly from the homogenized (CE_{ppt}) series (Figure 8(a)). Over the 1814–1978 period (where replication for both climate series includes at least four records and EPS >0.70; this period also encompasses the reconstructed dry conditions starting from *ca* 1830) the correlations between the 15-year filtered series derived from the reconstruction and the CE_{ppt} and CEU_{ppt} records are 0.43 ($p = 0.30$) and 0.78 ($p = 0.09$) respectively. These results suggest that the homogeneity correction procedures utilized for the early periods in the precipitation records may have 'overcorrected' these data and removed low-frequency climate information. Other dendroclimatic studies have identified potential homogeneity problems in climate records (Hughes *et al*., 1984; Cleaveland and Stahle, 1989) and our results suggest that these long precipitation records should be carefully re-evaluated.

If one accepts the hypothesis that these early 19th century records have been overcorrected, then the RCS reconstruction indicates that the 1830–70 period was drier than the 20th century (Figure 8(b)). This interpretation discounts suggestions (Rolland *et al*., 1998; Spiecker, 1999) that the observed increase in spruce growth at low elevations in central Europe may be related to non-climatic factors such as CO_2 or nitrogen fertilization and/or changes in forest management practices. Discrimination between these

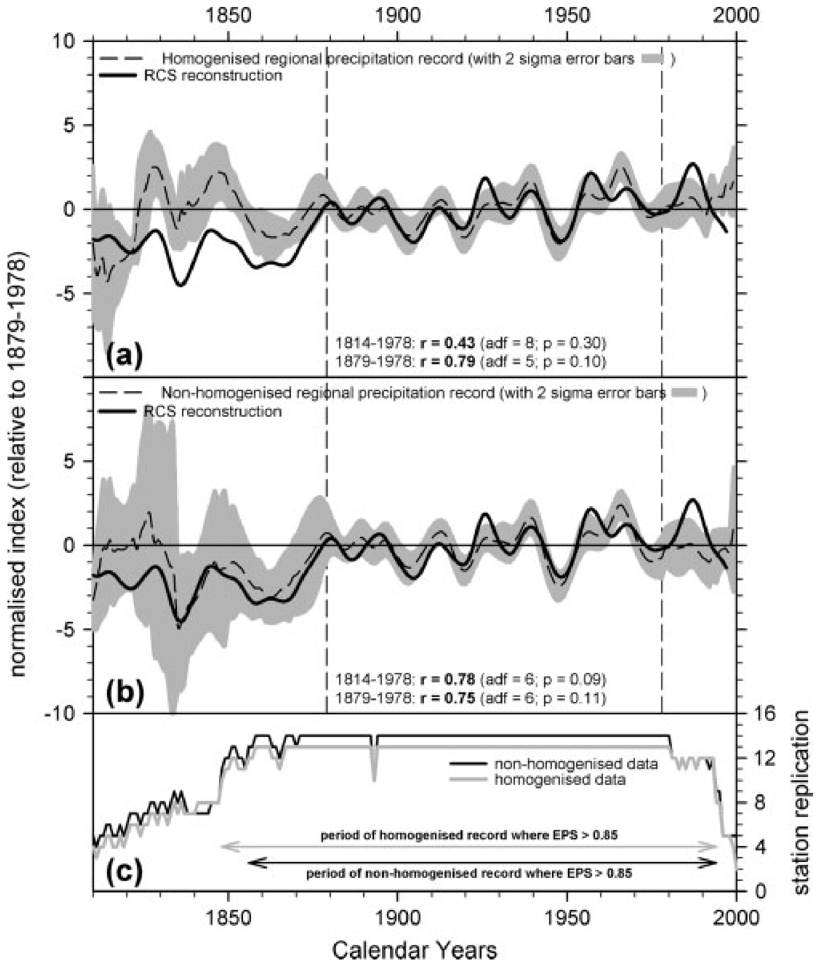

Figure 8. Comparison between low-pass-filtered series (15 year splines) of the RCS reconstruction with (a) the homogenized (CE_{ppt}; upper graph) and (b) non-homogenized (CEU_{ppt}; lower graph) regional precipitation series. The smoothed series have been scaled as z-scores to the 1879–1978 period (highlighted with the vertical dashed lines). The error bars (2 × standard error of mean) for the regional precipitation series, highlighted in grey, have themselves been scaled to the same reference period. The standard error values have been calculated from smoothed data of the original station records to ensure that the error bars are valid for the final mean smoothed series as uncertainty calculations are time-scale dependent. (c) Station record replication through time for each regional mean series. The arrows denote the period where EPS values for both records are >0.85 (Wigley *et al*., 1984; Briffa and Jones, 1990)

conflicting interpretations may be assisted by evaluation of other proxy records that are not influenced by anthropogenic activities.

5.2. Comparison with other proxy precipitation records

Correlations between the BF_{ppt} series and other long precipitation records in central Europe (Figure 2) suggest that one should also expect a reasonable amount of common variance between proxy records of precipitation from these same regions. Four proxy precipitation records have recently been developed for central Europe (Table IV). Luterbacher (personal communication) have reconstructed past monthly precipitation for a network of 0.5° × 0.5° grid squares (BERN) across Europe extending back to 1659 (Table IV). The BERN grid square reconstructions were developed by a canonical correlation analysis utilizing documentary sources and homogenized instrumental climate data from the target and neighbouring grid squares. Pfister (1992, 1995) reconstructed monthly indices for temperature and precipitation (CLH) for

Table IV. Precipitation reconstructions in central Europe

Code	Reference	Region	Proxy type	Seasonalized reconstruction	Length
RCS	This study	Bavarian Forest	Tree-ring	March–August	1480–2000
SPL	This study	Bavarian Forest	Tree-ring	March–August	1480–2000
BERN	Luterbacher (personal communication)	Bavarian Forest[a]	Documentary and climate data	All months	1659–1995
CLH	Pfister (1992, 1995)	Switzerland	Documentary	All months	1526–1989
BRT	Brázdil *et al.* (2002)	Southern Moravia, Czech Republic	Tree-ring	March–July	1376–1996
OBH	Oberhuber and Kofler (2002)	Upper Inn Valley, Austria	Tree-ring	April–June	1724–1997

[a] The BERN series used in this paper is the mean of two $0.5° \times 0.5°$ grid squares, centred at 49 °N, 12 °E and 49 °N, 12.5 °E, that are equivalent to the study region (Figure 2).

Switzerland back to 1525 using predominantly documentary sources and homogenized instrumental climate data. The CLH series were input into the data matrix from which BERN was generated (Luterbacher, personal communication, 2003), but the two final series differ considerably (Figure 9). Brázdil *et al.* (2002) and Oberhuber and Kofler (2002) have recently developed precipitation reconstructions (BRT and OBH respectively) from TR series. The BRT study reconstructs March–July precipitation totals (1376–1996) for southern Moravia in the Czech Republic using living and historic samples of *Abies alba* Mill. OBH reconstructed April–June precipitation back to 1724 using living samples of *Pinus sylvestris* L. from dry valleys in Austria. Visual and statistical comparison (Table V, Figures 9 and 10) of these records with the SPL and RCS reconstructions suggests they are most appropriately evaluated in two groups based on their frequency characteristics.

The RCS, BERN and CLH reconstructions all contain considerable low-frequency variability, though the relationships between these records vary over time (Figure 9). All three reconstructions indicate that the 20th century was relatively wet. However, the RCS chronology is better correlated with CLH over the 1780–1978 period, but with BERN over the longer 1659–1978 interval (Table V). The RCS and CLH records indicate drier conditions between *ca* 1800 and 1870, but the BERN reconstruction shows its highest values at this time. However, as BERN uses corrected precipitation records to reconstruct part of this interval, this discrepancy may reflect the homogenization problems referred to above. Glaser (2001) provides qualitative verification of this early 19th century dry period from spring and summer precipitation reconstructions developed using other documentary sources in central Europe. As these (and Pfister's) sources are independent of the Bavarian Forest reconstructions, they confirm the reconstructed drier conditions in the RCS reconstruction during the early to mid 19th century. Between *ca* 1650 and 1750 the RCS and BERN reconstructions show generally low precipitation values that are not seen in the CLH reconstruction. These differences in the reconstructions prior to *ca* 1750 can only be resolved with further work and closer examination of the nature of the differing proxy records utilized.

The TR data in the BRT and OBH chronologies were standardized using flexible digital spline filters and, therefore, the resultant reconstructions are comparable to SPL, capturing mainly decadal or higher frequency information. The BRT and OBH reconstructions respectively explained 38% and 30% of the variance in their calibrations and are comparable in strength to the SPL (40%) and RCS (34%) models described above. The BRT, OBH and SPL reconstructions show periods with strong decadal similarities (Figure 10), although correlations between these records are relatively low (Table IV). The between-series correlation varies over time, but decadal trends are synchronous over the 1500–40 and 1675–1900 intervals for SPL and BRT (Figure 10(a)) and from 1800 to 1950 for SPL and OBH (Figure 10(c)). The poor match between SPL

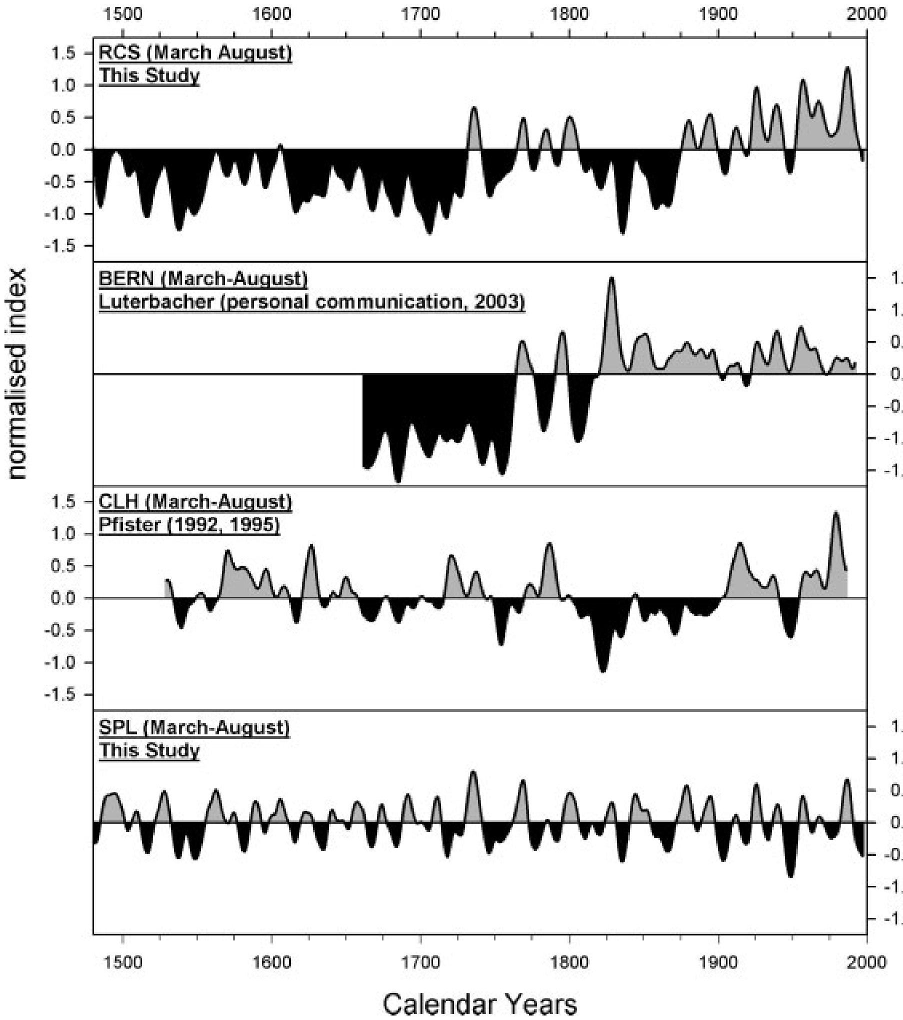

Figure 9. Low-pass-filtered time series (15 year cubic smoothing spline; Cook and Peters, 1981) of spring–summer precipitation reconstructions from central Europe. Prior to smoothing, the series were normalized relative to the common period (1724–1989) of all the proxy records (see Table IV)

and OBH prior to 1800 is probably due to low sample replication in the OBH record (Oberhuber and Kofler, 2002).

Comparison of the SPL, BRT and OBH series indicates common patterns in decadal-scale precipitation variability over the Bavaria–Moravia–Austrian region (Figures 2 and 10). Moreover, the SPL and BRT series are significantly correlated between *ca* 1500–50 and 1680–1850 (Figure 10(b)). This agreement provides some degree of mutual verification of these reconstructions at annual–decadal time scales. However, these similarities are not apparent when the RCS reconstruction is compared with the BRT and OBH reconstructions (Figure 9). This underscores the standardization problem defined by the 'segment length curse' (Cook *et al.*, 1995). Traditional standardization of chronologies with relatively short TR series, or using flexible splines, fails to capture low-frequency trends from these data that may be of considerable importance in characterizing the precipitation regime. Although RCS and SPL are statistically comparable robust reconstructions, they portray quite different patterns of precipitation variability and past history. They also have profoundly different implications for the modelling of future precipitation variability in this region: superimposition of the annual–decadal pattern onto low-frequency trends could result in

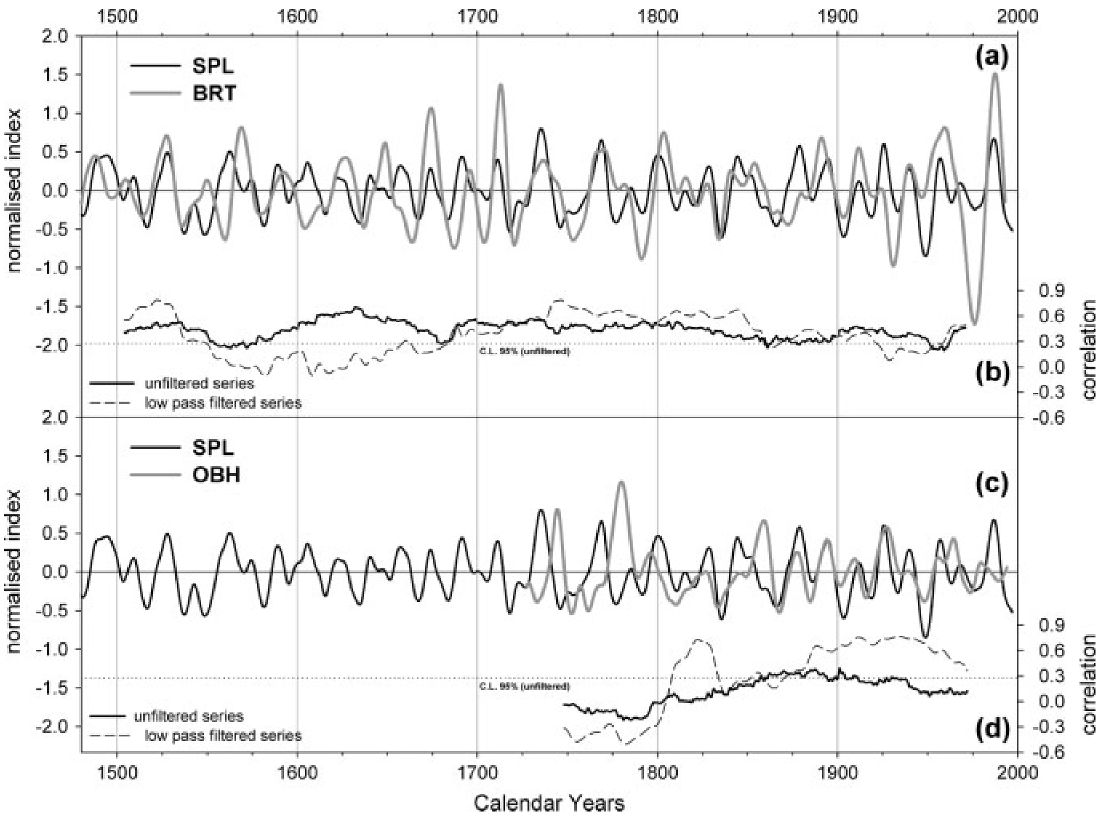

Figure 10. (a) Comparison between low-pass-filtered series of SPL and BRT. Prior to smoothing, the series were normalized relative to the common period (1724–1989) of all the proxy records (see Table IV). (b) The lower panel shows moving 50-year correlations for both unfiltered (black line) and low-pass-filtered (dashed line) series. The 95% confidence level for the unfiltered correlations is 0.278 (two-tailed; dotted line); (c) and (d) As (a) and (b) but comparing SPL and OBH

Table V. Correlations between the Bavarian Forest and other central European reconstructions of spring–summer precipitation over the periods 1780–1978 and 1659–1978. For abbreviations see Table IV. All correlations involving unfiltered data are significant at the 95% confidence level

		Unfiltered series				Low-pass-filtered series[a]			
		BERN	CLH	BRT	OBH	BERN	CLH	BRT	OBH
1780–1978	RCS	0.35	0.40	0.32	0.29	0.05	0.54	0.21	0.34
	SPL	0.46	0.35	0.34	0.34	0.27	0.12	0.35	0.35
1659–1978	RCS	0.43	0.32	0.30		0.48	0.41	0.20	
	SPL	0.34	0.29	0.33		0.18	0.12	0.41	

[a] The series were filtered with a 15 year cubic smoothing spline and truncated to remove potential end effects. The adjusted degrees of freedom, taking into account the autocorrelation in the smoothed series (Pyper and Peterman, 1998), were not calculated to assess the significance of the correlations. The correlations merely provide a guide to the common low-frequency variability between the series.

significantly more extreme conditions than those anticipated solely from SPL, BRT or similar reconstructions.

Proxy climate data are approximations of instrumental climate data. Their signals have embedded differences that reflect the specific proxy used, the parameter/season reconstructed, and differences in data-processing methods that effect the resultant target frequency domain. Figures 6(d) and 8 indicate that the SPL and RCS series reconstruct decadal spring–summer variability very well, and over some periods there is good coherence in these reconstructions when compared with other series (Figures 9 and 10). However, the RCS reconstruction also demonstrates multidecadal to centennial-scale trends in precipitation variability that are not seen in the other TR-derived records. The RCS and CLH records, together with other data from Glaser (2001), verify drier conditions in the mid 19th century (Figure 9). Comparison of the low-frequency signals in the RCS, BERN and CLH records prior to 1700 shows no consistent pattern. The RCS and BERN reconstructions show dry conditions in the 16th/17th centuries, but the CLH record shows more variable and less extreme conditions. Therefore, owing to the paucity of other proxy reconstructions that portray secular-scale trends, it is not yet possible to assess the long-term trends in the RCS reconstruction prior to *ca* 1750. More proxy reconstructions need to be developed in central Europe that are specifically targeted to the capture of low-frequency information that could potentially verify the RCS reconstruction in the future. Therefore, it is critically important to develop and cross-verify these reconstructions with other proxies that can extract unambiguous low-frequency signals to corroborate these low-frequency trends.

6. CONCLUSION

This paper has demonstrated that statistically robust dendroclimatic reconstructions of March–August precipitation totals can be developed from living and historical TR material for the Bavarian Forest region in southeast Germany. Two reconstructions were developed using the same TR database but different standardization strategies. The SPL reconstruction used RW data standardized using a fixed 80 year spline resulting in a reconstruction that modelled only decadal or high-frequency variability. The RCS reconstruction utilized the same RW data, detrended (Mitchell, 1967; Cook *et al*., 1995; Briffa *et al*., 1996; Esper *et al*., 2003) to maximize the capture of low-frequency information. The SPL and RCS reconstructions explain 40% and 34% respectively of March–August precipitation in the calibration period. The SPL series models more of the spring–summer precipitation variability but does not capture the longer term variation seen in the RCS series. Moreover, the smoothed RCS reconstruction is a better fit to the Bavarian Forest instrumental data (BF_{ppt}) than the SPL series (Figure 6(d)) and reconstructs the drier conditions seen in uncorrected regional precipitation records (CEU_{ppt}) over the 1830–70 interval (Figure 8(b)). Further verification of this early 19th century dry period is made by qualitative comparison with CLH (Figure 9) and with other data from Glaser (2001). Prior to 1800, the RCS series reconstructs drier conditions in the periods 1510–60, 1610–35 and 1660–1730. The BERN series also shows comparable drier conditions in the 16th and 17th centuries. The RCS, BERN and CLH records also indicate that 20th century conditions are wetter than preceding centuries.

The results presented in this paper suggest that there is significant, hitherto unrecorded, decade–century-scale variation in precipitation in the Bavarian Forest and adjacent areas in central Europe over the last 500 years. The RCS reconstruction is the first dendroclimatic reconstruction in Europe to capture such low-frequency information and indicates that traditionally derived TR reconstructions in the region (e.g. BRT, OBH and SPL) are missing important low-frequency signals. The RCS reconstruction also indicates that 20th century spring–summer conditions have been wetter than at any other period over the preceding four centuries. This reconstruction agrees with the observed intensification of the global water cycle (Milly *et al*., 2002) and the predicted increase of precipitation in central Europe (e.g. Jones *et al*., 1997; Frei *et al*., 1998). However, the absence of substantial agreement in long-term trends between precipitation reconstructions presently available for central Europe prior to 1750 indicates that it will be necessary to develop several new long precipitation reconstructions from independent data to validate this scenario. It is critical that these reconstructions focus on archives and techniques that can maximize the capture of low-frequency precipitation variability.

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APPENDIX A: DEVELOPING AN APPROPRIATE RCS STRATEGY

Wilson *et al*. (2004) showed that significant low-frequency information could be captured using the RCS technique (Mitchell, 1967; Cook *et al*., 1995; Briffa *et al*., 1996; Esper *et al*., 2003) on age-defined populations with MSL values of as little as 50 years. However, selecting the age groups to be used is somewhat arbitrary and does not take into account the potential variation in growth trends that may occur due to differences in ecology between sites and changes of climate through time. The mean-age-aligned curves calculated for the eight living spruce chronologies in the Bavarian Forest region show a high degree of between-site variation (analysis not shown). These differences must be related to site ecology, as these chronologies roughly cover the same time period (and, therefore, the same climatic conditions). This creates a problem in developing age-aligned curves for historical series, as the growth site (and its ecological conditions) are unknown and, therefore, these site-related effects cannot be studied. To address this issue, the spruce RW series were screened by finding the best least-squares fit of each individual series with three different standardization options: negative exponential function, negative regression function or those series modelled either by a horizontal line or an increasing trend. In so doing, four groups of similar growth curve type were identified; (1) steeply sloping negative exponential functions (NEXP1); (2) negative exponential functions with a shallow slope (NEXP2); (3) negative slope regression function (NEG); (4) zero slope regression function (MEAN). The number of radii, their MSLs and the replication of each group differ through time (Figure A.1(a)) and there are temporal biases of these groups to different periods. For example, the NEXP1 group clusters around

Growth Type	No. of radii	MSL
NEXP1	236	71.6
NEXP2	225	84.1
NEG	99	77.7
MEAN	116	97.4

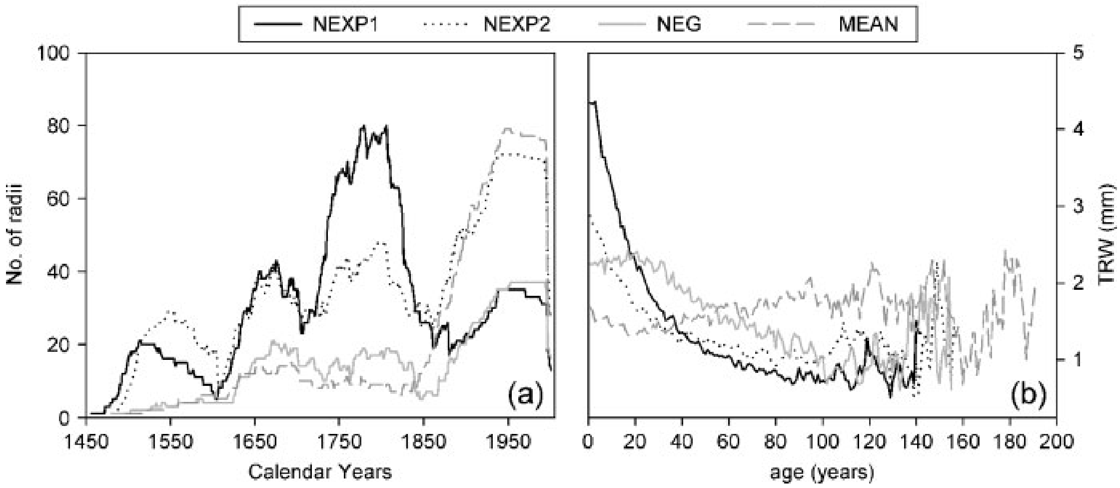

Figure A.1. Upper table: replication and mean sample (segment) length (MSL) in each growth type group. (a) Replication through time for each growth type group; (b) age-aligned mean curves

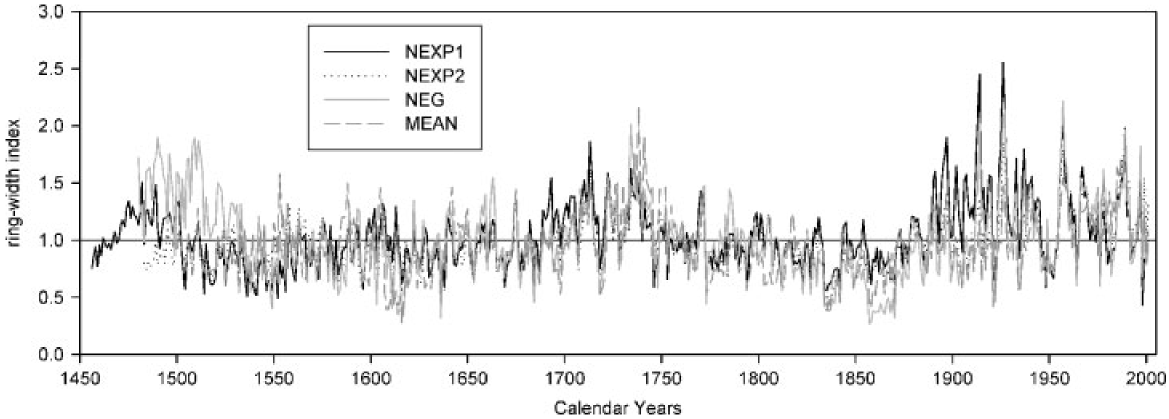

Figure A.2. Comparison of the growth-type grouped final RCS chronologies. Note the slight trend differences in the first half of the 18th century between the series in this figure and the final site equal-weighted RCS chronology in Figure 4. The series in this figure show a period of above-average index values from *ca* 1700–1750 that is related to the high replication (37 trees and 62 radii) in one historic TR site chronology that expresses higher growth levels than other RW series over this time period. Therefore, to reduce biased mean estimates in the final standardized chronologies (Figure 4), each historic/living site chronology was weighted equally

1730–1840, whereas the NEXP2 and MEAN groups are weighted to the living data. As would be expected, there are distinct differences between the age-aligned curves for each group (Figure A.1(b)). The difference in steepness between NEXP1 and NEXP2 is obvious. The NEG and MEAN aligned curves, although identified by linear modelling using regression functions, are in actual fact non-linear in nature. The NEG age-aligned curve shows relatively suppressed mean growth rates for the first 20 years and then a shallow negative exponential decrease. The MEAN age-aligned curve shows an initial decrease and then a slight increase in growth.

Four RCS chronologies were developed using the data from each of the growth type groups detailed in Figure A.1(a). An RC curve was developed for each group by fitting the curves in Figure A.1(b) with a cubic smoothing spline of 10% their length and using this curve to detrend the RW series in each of their respective groups. This is the same method used by Esper *et al*. (2003). There is a remarkable similarity between the four group chronologies (Figure A.2) which implies that the low-frequency trends captured using RCS are real and not an artefact of the detrending procedure. These trends compare well with the age-grouped RCS chronologies presented by Wilson *et al*. (2004). The only major differences are the first 40 years in the NEG group and the late 19th/early 20th century period in the NEXP1 group. In both cases, these deviations are possibly due to low replication (Figure A.1(a)) and do not pose a serious problem when all the data are combined to formulate one regional chronology.

REFERENCES

Auer I, Böem R, Schöner W. 2001. *Austrian long-term climate 1767–2000: multiple instrumental climate time series from central Europe*. Österreichische Beiträge zu Meteorologie und Geophysik, Heft 25, Publ. Nr. 397, Wien.

Baeriswyl P, Rebetez M. 1997. Regionalisation of precipitation in Switzerland by means of principal component analysis. *Theoretical and Applied Climatology* **58**: 31–41.

Beck C. 2000. *Zirkulationsdynamische Variabilität im Bereich Nordatlantik–Europa seit 1780*. Würzburger Geographische Arbeiten Heft 95, Würzburg.

Becker B. 1978. Dendroecological zones of central European forest communities. In *Dendrochronology in Europe*, Fletcher J (ed.). *British Archaeological Reports International Series* 51. Oxford: 59–64.

Becker M, Bert GD, Bouchon J, Dupouey JL, Picard JF, Ulrich E. 1995. Long term changes in forest productivity in north-eastern France: the dendroecological approach. In *Forest Decline and Atmospheric Depositions Effects in the French Mountains*, Landmann G, Bonneau M (eds). Springer Verlag: New York; 143–153.

Brázdil R. 1992. Climatic conditions of the Little Ice Age in Bohemia. In *Proceedings of the International Symposium on the Little Ice Age*, Mikami T (ed.).

Brázdil R. 1996. Reconstructions of past climate from historical sources in the Czech Lands. In *Climatic Variations and Forcing Mechanisms of the last 2000 Years*, Jones PD, Bradley RS, Jouzel J (eds). Springer-Verlag: Berlin.

Brázdil R, Stepánková P, Kyncl T, Kyncl J. 2002. Fir tree-ring reconstruction of March–July precipitation in southern Moravia (Czech Republic), A.D. 1376–1996. *Climate Research* **20**: 223–239.
Briffa KR. 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews* **19**: 87–105.
Briffa KR, Jones PD. 1990. Basic chronology statistics and assessment. In *Methods of Dendrochronology: Applications in the Environmental Sciences*, Cook ER, Kairiukstis LA (eds). Kluwer Academic Publishers: Dordrecht; 137–152.
Briffa KR, Jones PD, Bartholin TS, Eckstein D, Schweingruber FH, Karlen W, Zetterberg P, Eronen M. 1992. Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamics* **7**: 111–119.
Briffa KR, Jones PD, Schweingruber FH, Karlen W, Shiyatov G. 1996. Tree ring variables as proxy climate indicators: problems with low-frequency signals. In *Climatic Variations and Forcing Mechanisms of the last 2000 Years*, Jones PD, Bradley RS, Jouzel J (eds). Springer-Verlag: Berlin.
Cleaveland MK, Stahle DW. 1989. Tree ring analysis of surplus and deficit runoff in the White River, Arkansas. *Water Resources Research* **25**(6): 1391–1401.
Cook ER, Peters K. 1981. The smoothing spline: a new approach to standardising forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* **41**: 45–54.
Cook ER, Peters K. 1997. Calculating unbiased tree-ring indices for the study of climate and environmental change. *The Holocene* **7**(3): 361–370.
Cook ER, Briffa KR, Jones PD. 1994. Spatial regression methods in dendroclimatology: a review and comparison of two techniques. *International Journal of Climatology* **14**: 379–402.
Cook ER, Briffa KR, Meko DM, Graybill DA, Funkhouser G. 1995. The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene* **5**: 229–237.
Cook ER, Meko DM, Stahle DW, Cleaveland MK. 1999. Drought reconstructions for the continental United States. *Journal of Climate* **12**: 1145–1162.
Cook ER, Krusic, PJ, Jones PD. 2003. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. *International Journal of Climatology* **23**: 707–732.
D'Arrigo RD, Jacoby GC. 1991. A 1000-year record of winter precipitation from northwestern new Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the southern oscillation. *The Holocene* **1**(2): 95–101.
Dittmar C, Elling W. 1999. Jahrringbreite von Fichte und Buche in Abhaengigkeit von Witterung und Hoehenlage. *Forstwissenschaftliches Centralblatt* **118**: 251–270.
Esper J, Cook E, Peters K, Krusic P, Schweingruber F. 2003. Detecting low-frequency tree-ring trends by the RCS method. *Tree-Ring Research* **59**: 81–98.
Frei C, Schär C, Lüthi D, Davies HC. 1998. Heavy precipitation processes in a warmer climate. *Geophysical Research Letters* **25**(9): 1431–1434.
Fritts HC. 1976. *Tree Rings and Climate*. Academic Press: London.
Glaser R. 1998. Historische Hochwässer im Maingebiet — Möglichkeiten und Perspektiven auf der Basis der Historischen Klimadatenbank Deutschland (HISKLD). *Erfurter Geographische Arbeiten* **7**: 109–128.
Glaser R. 2001. *Klimageschichte Mitteleuropas. 1000 Jahre Wetter, Klima, Katastrophen*. Primus Verlag.
Herzog J, Müller-Westermeier G. 1998. Homogenitätsprüfung und Homogenisierung klimatologischer Meβreihen im Deutschen Wetterdienst. Internal Report for German Weather Service (DWD).
Hughes MK, Schweingruber FH, Cartwright D, Kelly PM. 1984. July–August temperature at Edinburgh between 1721 and 1975 from tree-ring density and width data. *Nature* **308**: 341–344.
Jones PD, Hulme M. 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology* **16**: 361–377.
Jones RG, Murphy JM, Noguer M, Keen AB. 1997. Simulation of climate change over Europe using a nested regional-climate model. Part II: comparison of driving and regional model responses to a doubling of carbon dioxide. *Quarterly Journal of the Royal Meteorological Society* **123**: 265–292.
Kohler MA. 1949. Double-mass analysis for testing the consistency of records and for making adjustments. *Bulletin of the American Meteorological Society* **30**: 188–189.
Lara A, Villalba R, Aravena JC, Luckman BH, Wolodarsky A, Wilson RJS. 2001. Dendrochronological studies of *Nothofagus pumilo* at tree-line in central Chile. *Canadian Journal of Forest Research* **31**: 925–936.
McCuen RH. 1985. *Statistical Methods for Engineers*. Prentice-Hall: New Jersey.
Milly PCD, Wetherald RT, Dunne KA, Delworth TL. 2002. Increasing risk of great floods in a changing climate. *Nature* **415**: 514–517.
Mitchell VL. 1967. An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest. Technical Report No. 33. University of Wisconsin, Department of Meteorology, Wisconsin.
Oberhuber W, Kofler W. 2002. Dendroclimatological spring rainfall reconstruction for an inner alpine dry valley. *Theoretical and Applied Climatology* **71**: 97–106.
Osborn TJ, Briffa KB, Jones PD. 1997. Adjusting variance for sample size in tree-ring chronologies and other regional mean timeseries. *Dendrochronologia* **15**: 89–99.
Pederson N, Jacoby GC, D'Arrigo RD, Cook ER, Buckley BM, Dugarjav C, Mijiddorj R. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: AD 1651–1995. *Journal of Climate* **14**: 872–881.
Pfister C. 1992. Five centuries of little ice age climate in western Europe. In *Proceedings of the International Symposium on the Little Ice Age*, Mikami T (ed.).
Pfister C. 1995. Monthly temperature and precipitation in central Europe from 1525–1979: quantifying documentary evidence on weather and its effects. In *Climate Since AD 1500*, Bradley RS, Jones PD (eds). Routledge: London.
Pfister C. 1999. *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen 1496–1995*. Haupt-Verlag: Bern.
Pyper BJ, Peterman RM. 1998. Comparison of methods to account for autocorrelation in correlation analyses of fish data. *Canadian Journal of Fisheries and Aquatic Sciences* **55**: 2127–2140.
Richman MB. 1986. Rotation of principal components. *Journal of Climatology* **6**: 293–335.

Richter K, Eckstein D. 1990. A proxy summer rainfall record for southeast Spain derived from living and historic pine trees. *Dendrochronologia* **8**: 76–82.

Rolland C, Petitcolas V, Michalet R. 1998. Changes in radial tree growth for *Picea abies, Larix decidua*, *Pinus cembra* and *Pinus uncinata* near the alpine timberline since 1750. *Trees: Structure and Function* **13**: 40–53.

Schweingruber FH, Bartholin T, Schär E, Briffa KR. 1988. Radiodensitometric–dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas* **17**: 559–566.

Spiecker H. 1999. Overview of recent growth trends in European forests. *Water, Air and Soil Pollution* **116**: 33–46.

Stahle DW, Cleaveland MK. 1992. Reconstruction and analysis of spring rainfall over the southeastern U.S. for the past 1000 years. *Bulletin of the American Meteorological Society* **73**: 1947–1961.

St George S, Nielsen E. 2002. Hydroclimatic change in southern Manitoba since A.D. 1409 inferred from tree rings. *Quaternary Research* **58**(2): 103–111.

Ulbrich U, Brücher T, Fink A, Leckebusch G, Krüger A, Pinto J. 2003a. The central European floods in August 2002. Part I: rainfall periods and flood development. *Weather* **58**(10): 371–376.

Ulbrich U, Brücher T, Fink A, Leckebusch G, Krüger A, Pinto J. 2003b. The central European floods in August 2002. Part II: synoptic causes and considerations with respect to climate change. *Weather* **58**(11): 434–441.

Vogel G. 2002. Labs spared as climate change gets top billing. *Science* **297**(5585): 1256.

Von Jazewitsch W. 1961. Zur klimatologischen Auswertung von Jahrringkurven. *Forstwissenschaftliches Centralblatt* **80**: 175–190.

Watson E, Luckman BH. 2001. Dendroclimatic reconstruction of precipitation for sites in the Canadian Rockies. *The Holocene* **11**(2): 203–213.

Wigley TML, Briffa KR, Jones PD. 1984. On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology* **23**: 201–213.

Wilson RJS. 2003. Assessment of historical tree-ring material for dendroclimatic purposes in the Bavarian Forest, Germany. Unpublished PhD thesis, University of Western Ontario.

Wilson RJS, Elling W. 2004. Temporal instabilities of tree-growth/climate response in the lower Bavarian Forest region: implications for dendroclimatic reconstruction. *Trees: Structure and Function* **18**(1): 19–28.

Wilson RJS, Hopfmueller M. 2001. Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany. *Dendrochronologia* **19**(1): 67–79.

Wilson RJS, Topham J. 2004. Violins and climate. *Theoretical and Applied Climatology* **77**: 9–24.

Wilson RJS, Esper J, Luckman BH. 2004. Utilising historical tree-ring data for dendroclimatology: a case Study from the Bavarian Forest, Germany. *Dendrochronologia* **21**(2): 53–68.

