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; Brázdíl 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 (BFppt)

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
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.

<table>
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<tr>
<th>Station code</th>
<th>Meteorological station</th>
<th>Elevation (m)</th>
<th>Record length</th>
<th>MEAN (mm)</th>
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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 (BFppt) 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

\[ n = \left( \frac{(r-1)\text{EPS}(x)}{r\text{EPS}(x)} \right) - 1 \]  

(1)

where the threshold value of EPS(x) is user defined and 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.
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$_{\text{ppt}}$ and CEU$_{\text{ppt}}$)

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$_{\text{ppt}}$) or uncorrected (CEU$_{\text{ppt}}$) data.

The correlation between the instrumental March–August precipitation series for BF$_{\text{ppt}}$ (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$_{\text{ppt}}$) 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 Brázdíl et al. (2002) and Oberhuber and Koßer (2002) TR reconstructions, BRT and OBH respectively (see Table IV)](image)
DENDROCLIMATIC RECONSTRUCTION OF GERMAN PRECIPITATION

indicate that precipitation patterns in BFppt 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 (CEppt and CEUppt) were
developed separately using the same Jones and Hulme (1996) procedures outlined above for the BFppt 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 CEppt and CEUppt with BFppt 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
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 \( \text{SO}_2 \) 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. Brázdíl 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).
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

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<td>1879–1978</td>
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<tr>
<td>1879–1978</td>
<td>0.60</td>
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</table>

$\text{Prec(March–August)} = 275.8 + 339.8TRW_t - 214.3TRW_{t+1} + 109.6TRW_{t+1}$

$\text{Prec(March–August)} = 229.9 + 302.3TRW_t - 147.4TRW_{t+1} + 100.9TRW_{t+1}$

$a$ $r$: correlation coefficient; $r^2$: explained variance; $\alpha R^2$: 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).

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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 $R^2$ 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. adjf: 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).
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 (CEppt and CEUppt) 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’ (CEUppt) instrumental data (Figure 8(b)), differing significantly from the homogenized (CEppt) 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 CEppt and CEUppt 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 CO2 or nitrogen fertilization and/or changes in forest management practices. Discrimination between these
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 BFpp 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 $0.5^\circ \times 0.5^\circ$ 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

<table>
<thead>
<tr>
<th>Code</th>
<th>Reference</th>
<th>Region</th>
<th>Proxy type</th>
<th>Seasonalized reconstruction</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS</td>
<td>This study</td>
<td>Bavarian Forest</td>
<td>Tree-ring</td>
<td>March–August</td>
<td>1480–2000</td>
</tr>
<tr>
<td>SPL</td>
<td>This study</td>
<td>Bavarian Forest</td>
<td>Tree-ring</td>
<td>March–August</td>
<td>1480–2000</td>
</tr>
<tr>
<td>BERN</td>
<td>Luterbacher (personal</td>
<td>Bavarian Forest</td>
<td>Documentary and climate data</td>
<td>All months</td>
<td>1659–1995</td>
</tr>
<tr>
<td></td>
<td>communication)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Czech Republic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Austria</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The BERN series used in this paper is the mean of two 0.5° × 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).
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.

<table>
<thead>
<tr>
<th></th>
<th>Unfiltered series</th>
<th>Low-pass-filtered series</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RCS</td>
<td>CLH</td>
</tr>
<tr>
<td>1780–1978</td>
<td>0.35</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.54</td>
</tr>
<tr>
<td>1659–1978</td>
<td>0.43</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>0.41</td>
</tr>
</tbody>
</table>

*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 utilized the same 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 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

<table>
<thead>
<tr>
<th>Growth Type</th>
<th>No. of radii</th>
<th>MSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEXP1</td>
<td>236</td>
<td>71.6</td>
</tr>
<tr>
<td>NEXP2</td>
<td>225</td>
<td>84.1</td>
</tr>
<tr>
<td>NEG</td>
<td>99</td>
<td>77.7</td>
</tr>
<tr>
<td>MEAN</td>
<td>116</td>
<td>97.4</td>
</tr>
</tbody>
</table>

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
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.

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