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Violins and climate

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With 8 Figures

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Summary

This paper explores the possibility of using ring-width measurements derived from string instruments as a potential source of palaeoclimate information. From a data-base of 1800 measured series, we have identified two sub-sets that compare well with living high elevation spruce (*Picea abies* (L.) Karst) chronologies from the Bavarian Forest and Austrian Alps. The problems of using historical tree-ring data for dendroclimatic purposes are addressed and by combining the living and historic ring-width data from these two regions, a preliminary proxy of past June/July mean temperatures is developed. This proxy summer temperature record shows striking similarities with a tree-ring based temperature reconstruction for the Central Eastern Alps, the CLIMHIST June/July temperature record from Switzerland and glacial records from the Austrian Alps. This explorative study demonstrates that ring-width series from string instruments may allow the identification of generalised source regions of wood used for instrument making and, most importantly, provide a new unique source for palaeoclimate information at a variety of both temporal and spatial scales for high elevations in central Europe.

1. Introduction

The development of long tree-ring (TR) reconstructions of climate in central Europe is hampered by the lack of long-lived trees. Most trees at high elevations rarely exceed 200–300 years in age (Eckstein, 1982) and longer chronologies must be developed by the use of cross-dated material from *in situ* sub-fossil wood or historic construction material (e.g. beams). Abundant *in situ* wood is rare in Europe and only found in very special circumstances (e.g. preserved in lake sediments (Grabner et al., 2001) or as sub-fossil material in glacial forefields (Nicolussi and Patzelt, 1996)). However, there is abundantly preserved historical wood. The use of historical TR material for dendroclimate work presents several problems (Wilson et al., submitted) – not the least of which is the provenance of the wood. Long living/historic composite chronologies may provide a continuous series for dating, but it is difficult to establish whether the earlier portions of the chronology represent trees growing in similar ecological or altitudinal settings as the living trees (Pilcher, 1982) and therefore contain a comparable climate signal.

Wilson and Hopfmueller (2001) identified statistically distinct signals in living Norway spruce (*Picea abies* (L.) Karst) ring-width (RW) data from trees growing at sites of different elevations in the Bavarian Forest (Fig. 1). This work resulted in a new strategy for dendrohistorical dating in the region. The change in growth/climate response of spruce with elevation necessitates the development of distinct chronologies for different elevational ranges, specifically

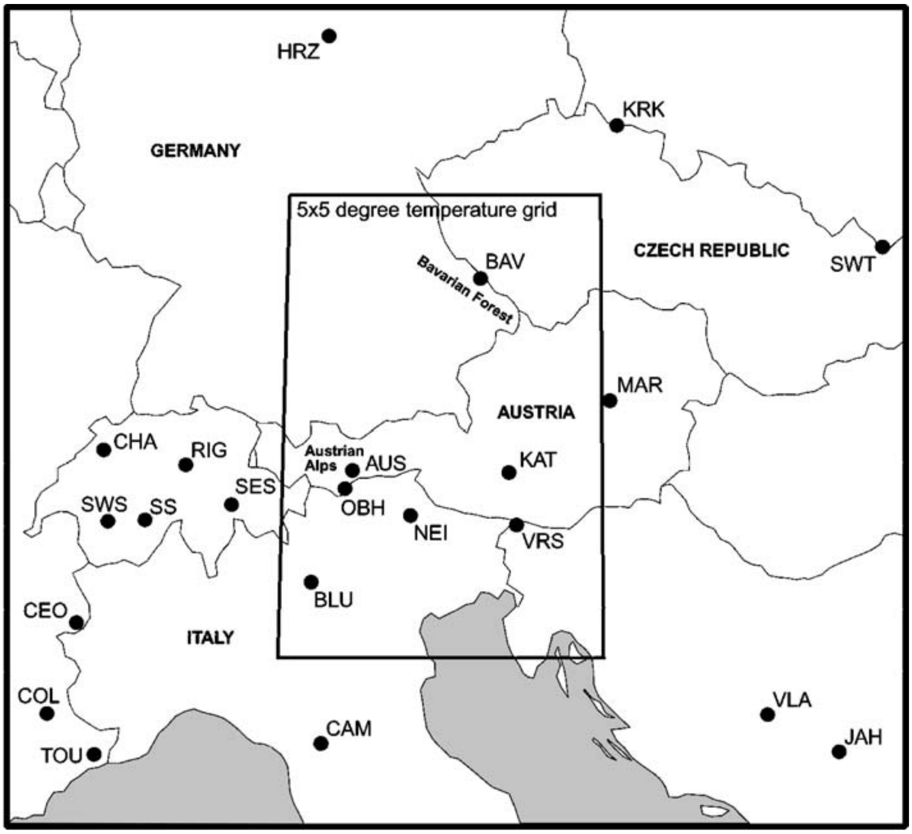

Fig. 1. Location map showing the Bavarian Forest, Austrian Alps, the 21 high elevation spruce chronologies used in this study and the 5° × 5° grid from which mean temperature data were used. Site codes are defined in Table 1

<700 m.a.s.l., >1050 m.a.s.l. and between 700–1050 m.a.s.l., in this region. Wilson and Hopfmueller (2001) concluded that it was unlikely that a well replicated high elevation living/historic composite spruce chronology could be developed in the Bavarian Forest because of the lack of buildings above ca. 1050 m.a.s.l. However, a solution may come from an unlikely source. Over the last decade, a database of ca. 1800 dated RW series measured from the fronts of string instruments (predominantly violins and cellos) has been developed (Topham, 2000; Topham and McCormick, 1997, 1998). The majority of these data are spruce and correlate well with high elevation living chronologies in central Europe. As high elevation living conifer chronologies have been shown to predominantly express a summer temperature signal (Briffa et al., 2002), it can be hypothesised that any historical TR data used to extend high elevation living TR data may also portray a summer temperature signal and could potentially be an invaluable palaeoclimate data source. The present paper assesses the dendroclimatological potential of these historical data. If successful, this ‘‘violin’’ TR data-set may be used to develop a larger scale dendroclimatic reconstruction for central Europe.

2. Targeted study region

Schweingruber (1985) divided Europe into six[1] dendro-ecological zones using living high elevation conifer TR chronologies. His Alpine region includes Switzerland, western Austria, north–east Italy and southern Germany. This is a surprisingly large area, but shows that RW chronologies, when averaged over large regions, can portray a reasonably strong common signal, even through mountainous regions. However, it is likely that Schweingruber's (1985) defined Alpine region can be further broken down into smaller sub-regions of differing TR variability, which ultimately result from the spatial heterogeneity of temperature (Beck, 2000).

Topham and McCormick (2000), by dating string instruments, identified that the predominant source of wood for the string instruments measured was probably from the Alpine region

[1] Lappland, Scotland, Alps, Pyrenees, Southern Italy and Southern Carpathian.

of central Europe. They did not, however, provide any evidence as to the wood's original source elevation. As Wilson and Hopfmueller (2001) showed that spruce trees from their identified high elevation zone (>ca. 1050 m.a.s.l.) in the Bavarian Forest expressed a significant positive response with summer temperatures, any historical TR data that correlated well with these data could potentially be used to extend a proxy of past summer temperatures developed from these living high elevation data.

In this study, using between-series correlation analysis and careful 'bridging' of the historic TR series, two composite sub-sets of RW data have been identified from the database of ca. 1800 dated "violin" RW series, that compare well with high elevation spruce chronologies in the Bavarian Forest and the Austrian Alps (Fig. 1). We focus on these two regions because, (1) this study compliments an ongoing study using historical TR material in the Bavarian Forest (Wilson and Hopfmueller, 2001; Wilson et al., submitted); (2) a high elevation living/historic TR chronology already exists for the Austrian Alps (Siebenlist-Kerner, 1984) which facilitates the comparison of historical TR data in periods when no living data are available; (3) there is a reasonably strong common signal between high elevation spruce chronologies between these two regions; (4) both regions are situated within the same $5^\circ \times 5^\circ$ grid square (Fig. 1) from which mean temperature data (Jones, 1994; Parker et al., 1995; Nicholls et al., 1995) will be used for growth/climate analysis.

3. Provenance identification of grouped violin TR material

The regional provenance of the identified grouped violin chronologies was established using spatial correlation analysis against 21 high elevation spruce chronologies around the Alpine

Table 1. Summary information on the reference tree chronologies used in this study. All chronologies are of individual sites except the following composite series: *BAV* = Hochzell (1812–1996; 1208 m), Falkenstein (1635–1995; 1325 m) and Arber (1806–1997; 1420 m). *NEI* = Fodara vedla (1598–1990; 1970 m); Cortina dAmpezzo Nord/Sud (1660–1975; 1820–1900 m). *AUS* = Obergurgl (1789–1974; 2000 m); Stubaital (1745–1975; 1850 m). *SES* = Suaiza (1695–1988; 1520 m); Obersaxen, Meierhof (1537–1995; 1520 m); Arosa Nord/Sud (1690–1975; 1940–2000 m). *SS* = Burchen Bielwald (1707–1980; 1740 m); Mittleri Hellelawald (1793–1980; 1510 m); Tatz Stockwald (1769–1980; 1850 m); Lostschental (1768–1998; 1900 m); Riederalp (1778–1974; 2000 m); Grindelwald Nord/Sud (1774–1995; 1700–1960 m). *SWS* = Chable d.trois besses (1813–1979; 1520 m); Lauenen (982–1976; 1000–1700 m); Simmental, Iffigenalp (1532–1986; 1900 m; Simmental, St. Stephan (1690–1986; 1900 m). *CEO* = l' Orgere (1740–1973; 2100 m); Mt. Cenis (1834–1975; 1950 m). All data outside of the Bavarian Forest were downloaded from the International Tree-Ring Data-Bank (http://www.ngdc.noaa.gov/paleo/ftp-treering.html)

Site code	Site name	Elev (m.a.s.l.)	Chronology coverage	No. of series
HRZ	ANDREASBERG	900	1739–1977	14
KRK	KRKONOSE MTS North/South	1000–1300	1781–1991	107
SWT	SWISTOWKO	1500	1699–1978	15
BAV	BAVARIAN FOREST	1208–1420	1635–1997	116
MAR	MARIAZELL	1380	1832–1975	12
JAH	JAHORINA	1700	1736–1981	26
VLA	VLASIC	1600	1823–1981	24
VRS	VRSIC	1600	1757–1981	24
KAT	KATSCHERPASS	1800	1838–1975	12
NEI	NORTH–EAST ITALY	1900–1970	1660–1990	37
AUS	AUSTRIAN ALPS	1850–2000	1745–1975	37
OBH	OBERGURGL [historical TR data]	2000	1276–1870	89
CAM	CAMPOLINO	1650	1836–1988	24
BLU	BLUMONE	1650	1842–1980	16
SES	SOUTH–EAST SWITZERLAND	1520–2000	1537–1995	65
RIG	RIGI STAFFEL	1600	1840–1975	13
SS	SOUTH SWITZERLAND	1510–2000	1707–1998	167
CHA	CHASSERAL	1500	1839–1974	16
SWS	SOUTH–WEST SWITZERLAND	1000–1900	982–1986	272
CEO	MT. CENIS and L' ORGERE	1950–2100	1740–1975	29
COL	COL D'ALLOS	1900	1792–1975	10
TOU	LE TOURNAIRET	2050	1715–1977	26

region (Fig. 1 and Table 1). For chronology development, the raw RW data were processed by removing long term trends using a 30 year cubic smoothing spline and autoregressive modelling (i.e. pre-whitened; Cook and Peters, 1981; Cook, 1985). The resultant chronologies are therefore biased towards the high frequency domain. The replication and full chronology coverage for the violin TR data groups that compare with the Bavarian Forest (Group 1) and Austrian Alps (Group 2) are presented in Fig. 2. It is clear from this figure that the overlap between the different data-sets is almost always during the least replicated periods for each chronology, which will likely bias the correlation analysis results due to weak signal strength during these periods. The correlations were therefore calculated using both the maximum overlap period between bivariate pairs and the period 1715–1859. This latter period is the common most replicated period between the longer chronologies in the network and provides some consistency in the spatial correlations that might be lacking when using the maximum overlap period.

Figure 3 presents the results from the spatial correlation analysis and shows that the Group 1 chronology correlates best with the BAV chronology in the Bavarian Forest, and that the Group 2 chronology correlates best with the AUS chronology from the Austrian Alps. It should also be noted, however, that both the Group 1 and Group 2 chronologies also correlate well with the SWS chronology. As there is no significant difference (using a t-test) between these correlations, we can not definitively say from these correlation results that the Group 1 and Group 2 data-sets express high elevation spruce RW variability for the Bavarian Forest and Austrian Alps respectively. However, the strong correlations between the "violin" TR data and the BAV, AUS and SWS chronologies imply that there is a strong common signal in the high elevation TR data across the region and that the "violin" TR data express this

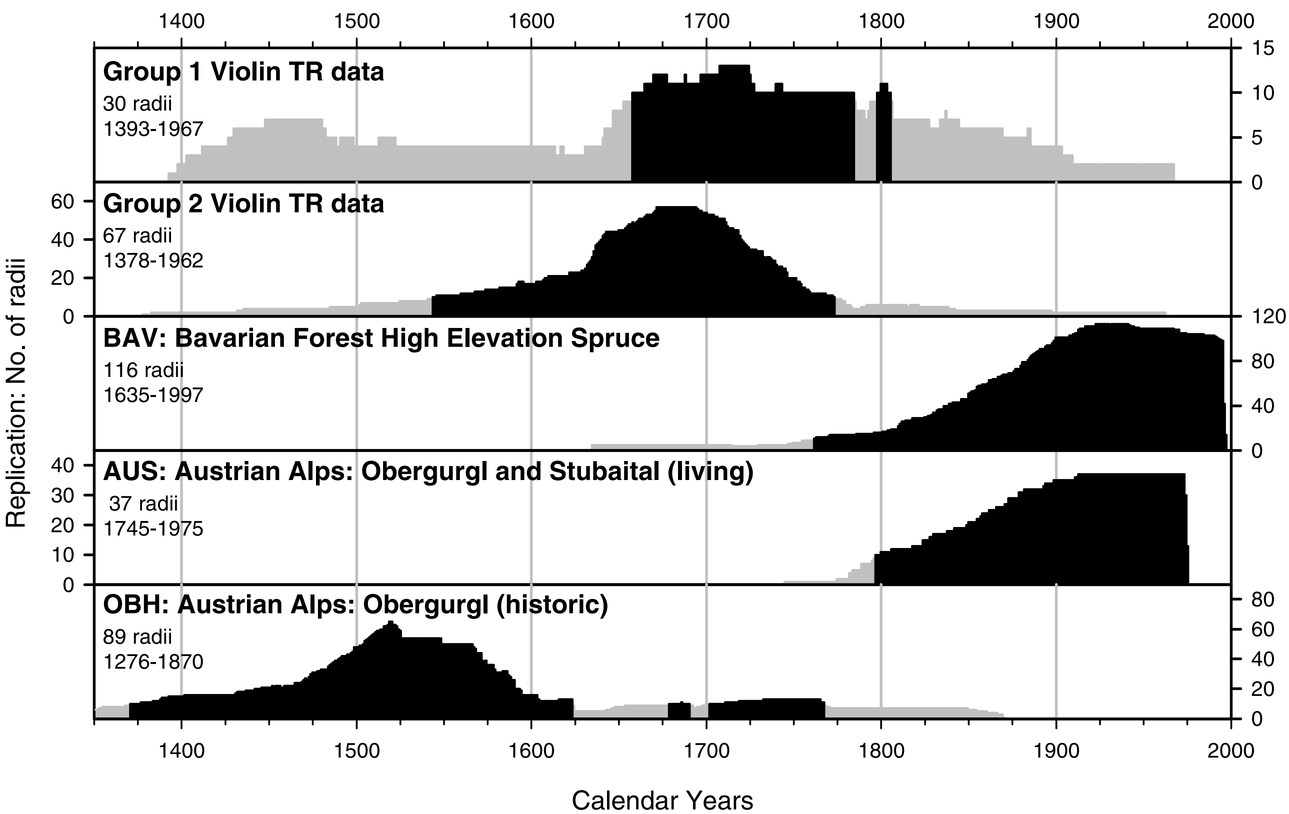

Fig. 2. Replication and chronology coverage of the violin historic RW data that group with the Bavarian Forest (Group 1) and Austrian Alps (Group 2). The replication of the living data from these regions is also presented along with the Siebenlist-Kerner (1984) historic RW data from the Austrian Alps. Replication of 10 series or higher is shaded in black to highlight those periods of reasonable signal strength in the chronologies

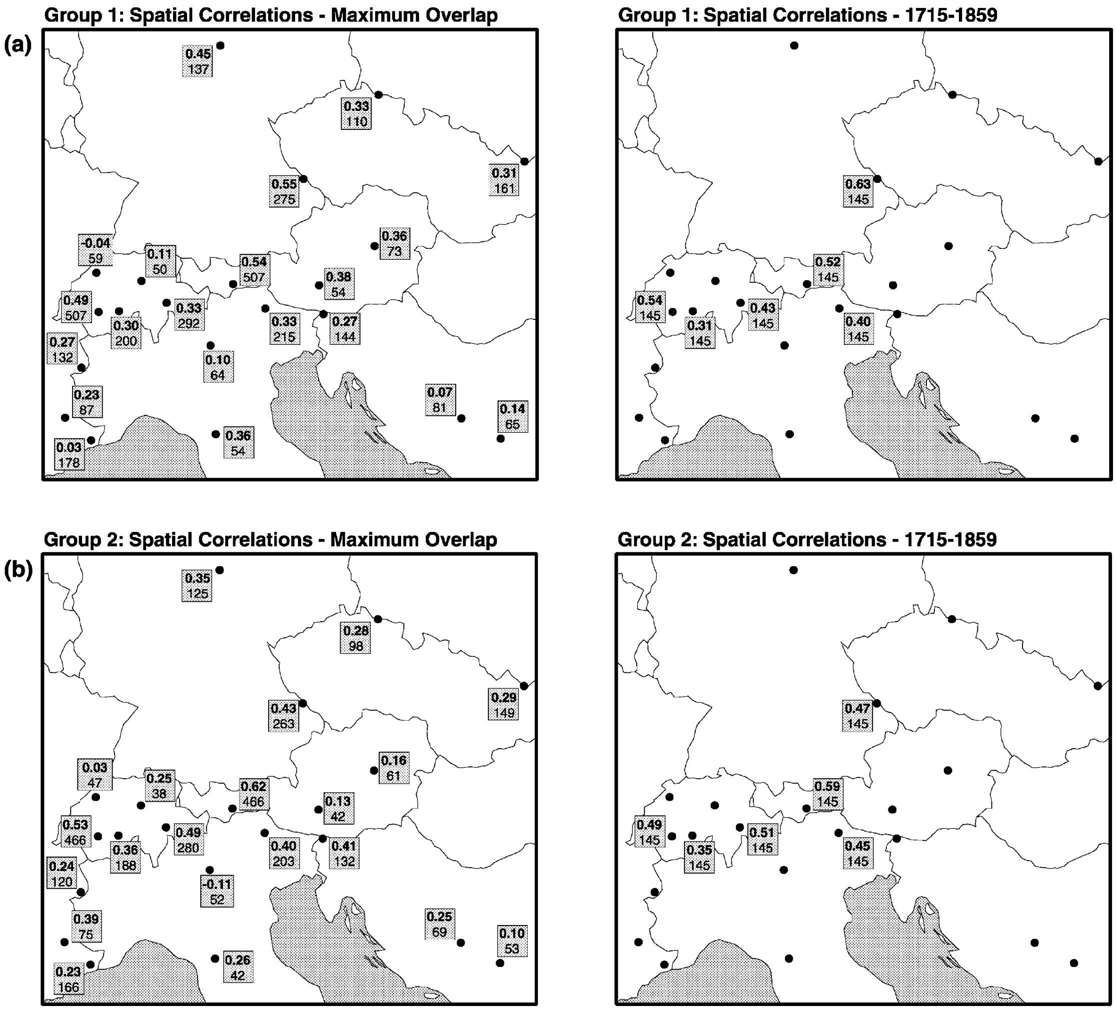

Fig. 3. Spatial correlation analysis of the Group1 (**a**) and Group 2 (**b**) violin historic chronologies. In each square, the upper value denotes the correlation of the group chronology with that particular high elevation site and the lower number denotes the degrees of freedom. Correlations were calculated over periods with a minimum of 3 radii

Table 2. Instrument types and location of instrument makers for the data included in Groups 1 and 2. Note the total number of instruments is less than the total number of series for each group as more than one series (i.e. both bass and treble boards) was measured from the fronts of the instruments

Nationality	Violins	Violas	Cellos	Lutes	Guitars	Bass viol	Cittern	Total
Group 1								
English	2	1	4	0	2	1	0	10
German	4	0	0	1	0	0	0	5
Italian	2	1	2	0	1	0	1	7
French	1	0	0	0	0	0	0	1
Total	9	2	6	1	3	1	1	23

Nationality	Violins	Violas	Cellos	Lutes	Bass viol	Vd'Amore	Total
Group 2							
English	6	3	15	0	0	1	25
German	4	0	0	1	1	0	6
Italian	17	1	1	0	1	0	20
French	3	0	1	0	0	0	4
Total	30	4	17	1	2	1	55

same large scale signal which presumably is forced by climate (summer temperatures).

The spatial correlation analysis results indicate, therefore, that the wood from the examined instruments included in Groups 1 and 2 originally came from high elevations in central Europe. Table 2 details the kind of instruments analysed for Groups 1 and 2 and which countries the instrument makers were located. If the Group 1 and 2 data do indeed portray high elevation spruce RW variability from the broad regions around the Bavarian Forest and Austrian Alps, there appears, therefore, little correlation between the location of the maker and the location of the source wood. For example, for the examined instruments made in England, wood has obviously been imported from central Europe. This is potentially an important preliminary observation. These results suggest that it cannot be assumed that instrument makers used only local wood. However, this observation must remain preliminary at this stage and a more definitive conclusion can only be made when the full "violin" TR data-base is examined.

It should also be stressed that identifying provenance of historical TR material, using spatial correlation analysis (Fig. 3), is problematic. Firstly, site ecological conditions, and therefore chronology quality with respect to climate, is not always known for reference chronologies. For example, the CHA, RIG and BLU chronologies show low, non-significant correlations with both the Group 1 and Group 2 data-sets that do not 'fit in' with the general spatial correlation patterns (Fig. 3). Presumably, the chronologies from these sites either portray a signal from lower elevations or the RW series are affected by site specific factors. Secondly, the reference living chronologies rarely go back far enough to assess the signal of the historical TR data. The fact that the correlation results using the maximum overlap and the fixed period analysis (Fig. 3) are reasonably similar suggest that the observed correlation patterns are real. However, the spatial signal of the historical RW data cannot be properly assessed over earlier periods where there is little or no reference RW data of known location (either living or historical). Without suitable reference material, therefore, caution must therefore be advised to the 'identified' provenance of those samples prior to those periods where reference material is available. As yet, the only available long term high elevation spruce chronology is Siebenlist-Kerner's (1984) living/historic spruce composite chronology from Obergurgl (OBH; Table 1) and this alone cannot address the problem of provenance for the earlier series. The long SWS composite chronology (Table 1), which also includes many historical TR series sampled from around Lauenen in the Swiss Alps (Schweingruber et al., 1988), is unfortunately not particularly useful for identifying high elevation historical spruce material. Not only are fir TR series included in this historical data-set, but the hypothesised elevational range in these historical TR data is from 1000–1700 m.a.s.l. (Table 1) and therefore likely portray a mixed elevational signal in the RW data.

4. Comparison of statistical properties

The spatial correlation analysis in the previous section indicates that the Group 1 and Group 2 chronologies express a similar high frequency signal to high elevation spruce chronologies in the Bavarian Forest and Austrian Alps. The correlations between the Group 1 and Group 2 chronologies with the Bavarian Forest low elevation spruce living/historic composite chronology (Wilson and Elling, 2003; Wilson et al., submitted), over their common periods, are 0.01 ($p = 0.87$; 1456–1967) and −0.07 ($p = 0.13$; 1456–1962) respectively. These results indicate that the violin RW series do not portray a low elevation signal and the orthogonal relationship observed between high and low elevation chronologies in the Bavarian Forest over the 20th century (Wilson and Hopfmueller, 2001) hold for the last five centuries.

Wilson and Hopfmueller (2001) also showed that correlations between high elevation spruce chronologies and summer mean temperatures decrease markedly from 1400 m.a.s.l. to 1050 m. a.s.l. in the Bavarian Forest. Chronologies below ca. 1050 m.a.s.l. show no significant positive response with summer temperatures. The chronologies with the strongest response to temperature were above 1300 m.a.s.l. (Wilson and Hopfmueller, 2001). Kienast et al. (1987), in Switzerland, and Dittmar and Elling (1999), in Bavaria, also showed that chronologies located 200–300 metres below tree-line were less sensitive to temperature than those sampled higher up-slope. In dendroclimatology, site selection is one of the more important steps in the development of a climate reconstruction. For a reconstruction of past summer temperatures, it is standard practise to select an undisturbed, open canopied, upper tree-line site for TR sampling because tree-growth at such sites is normally predominantly controlled by temperature variations (Fritts, 1976). Unfortunately, although the results in Fig. 3 suggest that the Group 1 and Group 2 historic chronologies portray a high elevation signal, they do not indicate how close the source wood for the violins was to tree-line. If the trees originally grew 200–300 m below tree-line, these historical RW data might not portray the desired sensitivity to climate and hence may not be a good proxy data source to assess past temperatures.

Spruce growth in the Bavarian Forest varies with elevation and RW data from each of the different elevational zones have a unique set of statistical RW properties (Wilson and Hopfmueller, 2001). Wilson et al. (submitted) expanded upon this observation and successfully compared statistical properties between historical RW data and living RW data in the Bavarian Forest to indicate that historical TR data, sampled from historic buildings in the Danube Valley, originally came from low elevations (<700 m.a.s.l.).

Figure 4 compares mean RW and mean sensitivity statistics for living and historical RW chronologies from the Bavarian Forest and Austrian Alps. Two sigma error bars are presented to aid statistical comparison between the mean values. The Austrian Alps RW data are separated into living (AUS) and historic (OBH) sub-sets (Table 1). The mean statistics for the low (LOW) and intermediate (INT) elevation chronologies from the Bavarian Forest are presented for comparative purposes. On the whole, there is little statistical difference between the mean RW values of both the high elevation living (BAV and AUS) and historic (G1, OBH and G2) RW chronologies although the AUS data obviously came from trees with slower growth rates. On the whole, all five high elevation chronologies have significantly lower mean RW values than the LOW or INT chronologies from the Bavarian Forest suggesting that the historic violin RW data do indeed portray growth rates equivalent to those of high elevation trees. The relatively low mean RW values for the violin (G1 and G2) data are not surprising. String instrument makers traditionally use wood with narrow rings because it is stronger, and the denser wood improves the acoustic properties of the instruments (Peterlongo, 1980).

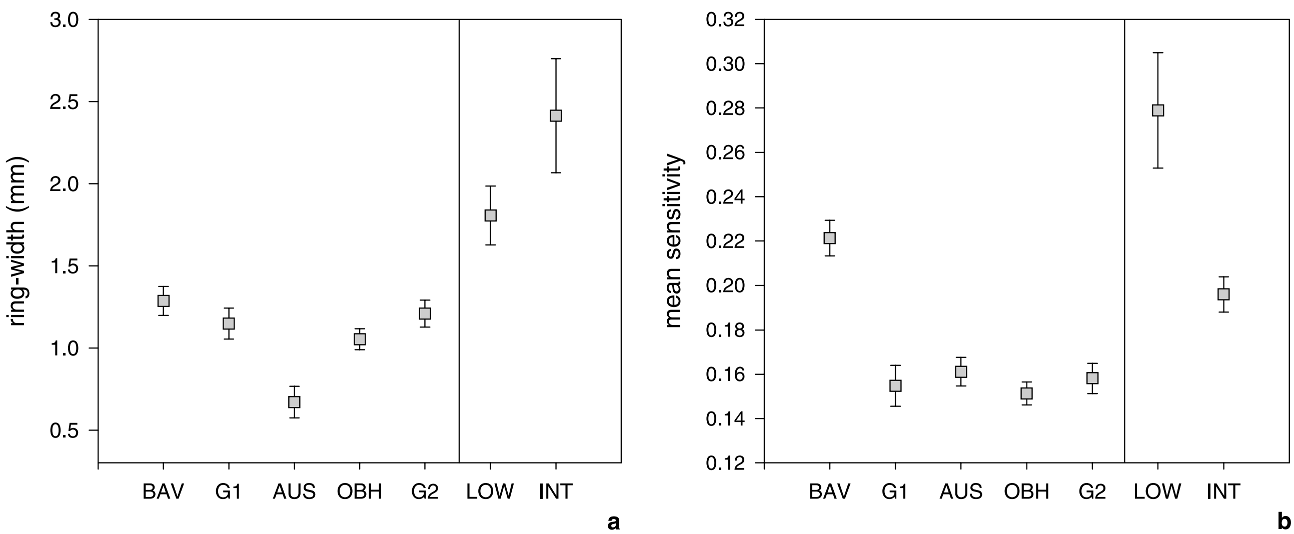

Fig. 4. Comparison of the mean values for ring-width (**a**) and mean sensitivity (**b**) for selected TR chronologies. The high elevation chronologies are BAV, Group 1 (G1), AUS, OBH and Group 2 (G2). The mean statistics for the chronologies of the Bavarian Forest low (LOW) and intermediate (INT) elevation zones (Wilson et al., submitted) are presented for comparative purposes. The 95% confidence range for each mean function is shown. Mean sensitivity measures the relative difference in ring-width from one ring to the next (Fritts, 1976)

It should be noted however, that elevation is not the only factor that can result in trees with varying growth rates (Fritts, 1976). However, as the Group 1 and Group 2 composite chronologies correlate with high elevation spruce data (Fig. 3) and not with low elevation spruce data, the comparable low growth rates between the historical and high elevation living spruce data (Fig. 4) simply provide further, albeit circumstantial, evidence that the 'violin' series are measured from high elevation wood.

The most striking difference in the results presented in Fig. 4 is in the mean sensitivity values. The mean sensitivity value for the BAV chronology is significantly higher (0.22 versus ca. 0.16) than the other high elevation living or historic chronologies (G1, AUS, OBH and G2) which might indicate that the BAV chronology is more sensitive to interannual climate variability. The low mean sensitivity values for the AUS chronology is particularly surprising as this site was presumably sampled at tree-line and represents one of the highest elevation living spruce chronologies utilised in this study (Table 1). The fact that the mean sensitivity values of the G1, AUS, OBH and G2 chronologies are much lower than the BAV chronology suggests that the trees may either, (i) have originally come from the lower end of the high elevation zone or, (ii) unknown site specific ecological factors at the original stands affected the trees in some way to lower their interannual sensitivity. Generally, large mean sensitivity values are considered desirable for dendroclimatic purposes as they indicate the presence of strong year-to-year variability (Fritts, 1976). Therefore, these low mean sensitivity values for the historical RW chronologies might have important implications for the use of these data for dendroclimatic work. However, it should be noted that although low values indicate that a chronology may not show a strong year-to-year response to climate, it still may be sensitive to low frequency climate variation.

Such ambiguous results therefore, probably indicate that comparison of chronology statistical properties may not always be a robust tool to provide information on the source elevation of RW chronologies and may only provide a rough guide for such identification. Similar ambiguous results (not shown) were also observed when the 1st order autocorrelation statistic was used for comparison.

5. Development and comparison of historic and living standardised chronologies

An important final step in assessing the signal in historic TR data is to compare historic and living chronologies over their period of overlap. If there is a reasonable agreement between the series at both high and lower frequencies, it can be assumed that the historic data can be used to extend the living data and that any transfer functions developed using the living data may also be valid for the historic TR data.

For this comparison, the tree-ring data were re-processed so that the resultant standardised chronologies captured interannual and multidecadal scale variability. There is no information on the original stand dynamics of the historical RW data and it is not known whether the trees originally grew in an open canopy or forest interior situation. Careful inspection of the raw RW series shows that many of the series show a juvenile increase in radial growth. To model this nonclimatic trend in the RW series, the Hugershoff function (Bräker, 1981) was used for standardisation. This function is a combination of a polynomial and negative exponential function and is more flexible than other deterministic models as it can fit both the early increase in growth and the falling trend of later years (Bräker, 1981; Cook et al., 1990). Prior to trend removal by subtracting the fitted Hugershoff function, the variance of the raw RW series was stabilised using an adaptive power transform (Cook and Peters, 1997). This method removes the potential 'end effect' inflation of index values that can occur when using standard 'ratio' detrending. For each living or historic chronology, the detrended series were averaged together using a biweight robust mean to diminish the effect of outliers on the mean function (Cook et al., 1990) and the chronology variance was stabilised temporally using techniques outlined in Osborn et al. (1997).

Standardised chronologies were developed for the combined Group 1 and Group 2 violin RW data plus the living RW data from BAV and AUS. The overlap period for the resultant historic and living composite chronologies is presented in Fig. 5a. It should be noted that the living data go back to 1635 while the historical RW data go forward to 1967 (Fig. 2). However, due to

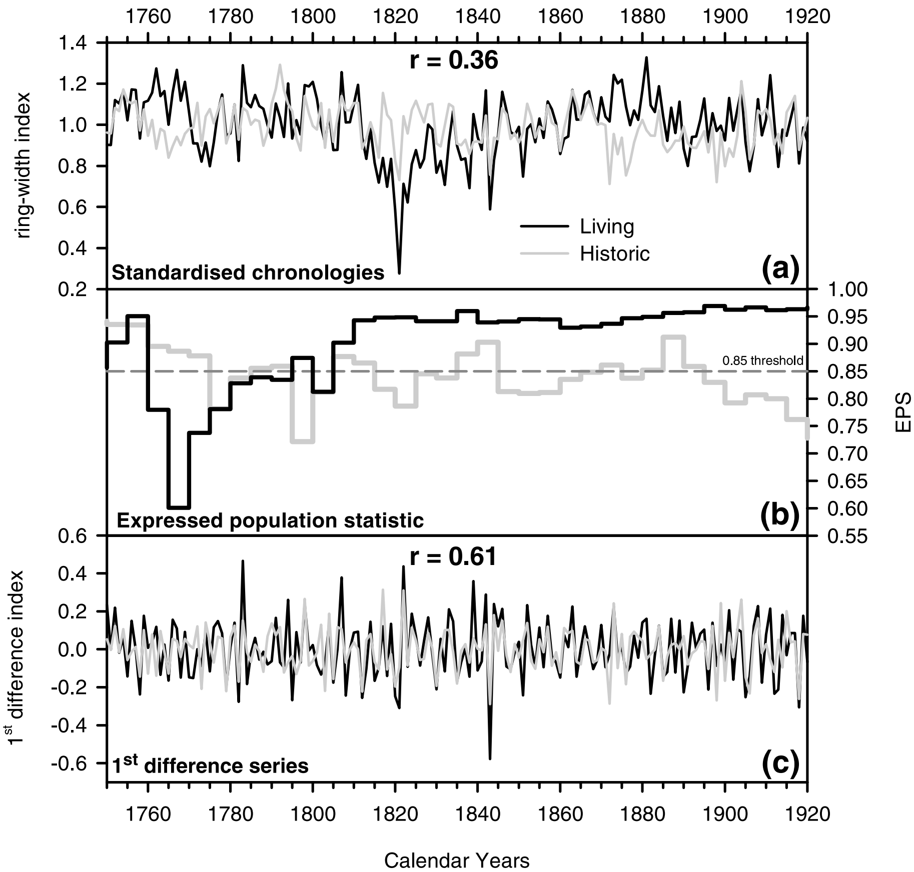

Fig. 5. (**a**) Comparison of the living and historic standardised RW chronologies over their period of mutually well replicated overlap. (**b**) Running 30 year (lagged by 5 years) EPS values for both chronologies. The EPS is a quantitative measure of how a 'sample' of RW series, when averaged together, portray a hypothetical perfect 'population' chronology. A value of 0.85 is generally considered adequate for dendroclimatic purposes (Briffa and Jones, 1990). (**c**) As 5a, but the series have been transformed to 1st differences

low replication at the extreme end of these series, the standard chronologies are only compared for that period where they both show a reasonably robust mean signal. The signal strength of the chronologies is assessed using the Expressed Population Statistic (EPS; Wigley et al., 1984; Briffa and Jones, 1990). The EPS, calculated for 30 year windows (lagged by five years), is presented in Fig. 5b for both chronologies. An 0.85 EPS threshold value is often cited as being a reasonable acceptance threshold (Briffa and Jones, 1990). Only between ca. 1760 and 1780 in the living TR data are the EPS values markedly lower than this threshold. Although the EPS values in the historic data are marginally below 0.85, they likely do not constitute a serious problem when comparing the two chronologies together.

The correlation between the standard chronologies is 0.36 (Fig. 5a). Although this value appears low, there are periods of strong synchroneity. The periods of divergence, which affect the overall correlation, are 1760–1770, 1815–1835 and 1870–1885, which appear to be related to trend differences rather than differences in interannual variability. When the chronologies are transformed to 1st differences, the between series correlation increases to 0.61 and the synchroneity of the common interannual signal between both chronologies is much stronger (Fig. 5c). Similar results are obtained when comparing the three high elevation chronologies that were included in the BAV data-set (Table 1). After standard chronologies of these sites are developed using the Hugershoff function, their mean between chronology correlation is 0.46 (using the period 1890–1995 where all three chronologies have an EPS >0.85). The mean between chronology correlation value increases to 0.76 when the chronologies are transformed to 1st differences. These mean correlation values between the three Bavarian chronologies are probably higher than those for the overlap period between the historic and living chronologies (Fig. 5) because of the relative distances between the chronologies. The maximum distance between the three Bavarian Forest living chronologies is ca. 15 km whereas the distance between the Bavarian Forest and Austrian Alps is ca. 250 km. As there will undoubtedly be a decay in common signal with increasing distance between chronologies (Rolland, 2002), it is not surprising that a weaker common signal is noted between the historic and living RW data as the data were 'sampled' over a relatively large region.

Although low replication and therefore weak signal strength, especially during the 1760–1770 period in the living data, might exacerbate the low correlations in Fig. 5, another possible reason for the divergence in trend between the historic and living chronologies (Fig. 5a) over the periods 1760–1770, 1815–1835 and 1870–1885 is due to removal of trend during the standardisation process. Cook et al. (1995) state that when undertaking TR standardisation, the lowest frequency of climate information that can be realistically recovered from a series is 3/n cycles per year (where n = the mean sample length (MSL)). This lowest frequency is known as the 'fundamental frequency' and is affected by the average length of the series within a chronology. This problem is known as the "segment length curse" (Cook et al., 1995). Over the 1750–1920 period shown in Fig. 5, the MSL for the living and historical RW data are ca. 200 and 120 years respectively. Therefore, using a standardisation procedure such as the Hugershoff function, more 'potential' lower frequency information will be removed from the historic RW data than the living RW data because of their lower MSL. The "segment length curse" might therefore be the cause of the relative 'flattening' of the historic chronology in Fig. 5a compared to the living chronology.

Overall however, although the mean sensitivity values in Fig. 4 suggest that the violin TR data may not portray a 'near tree-line' high elevation

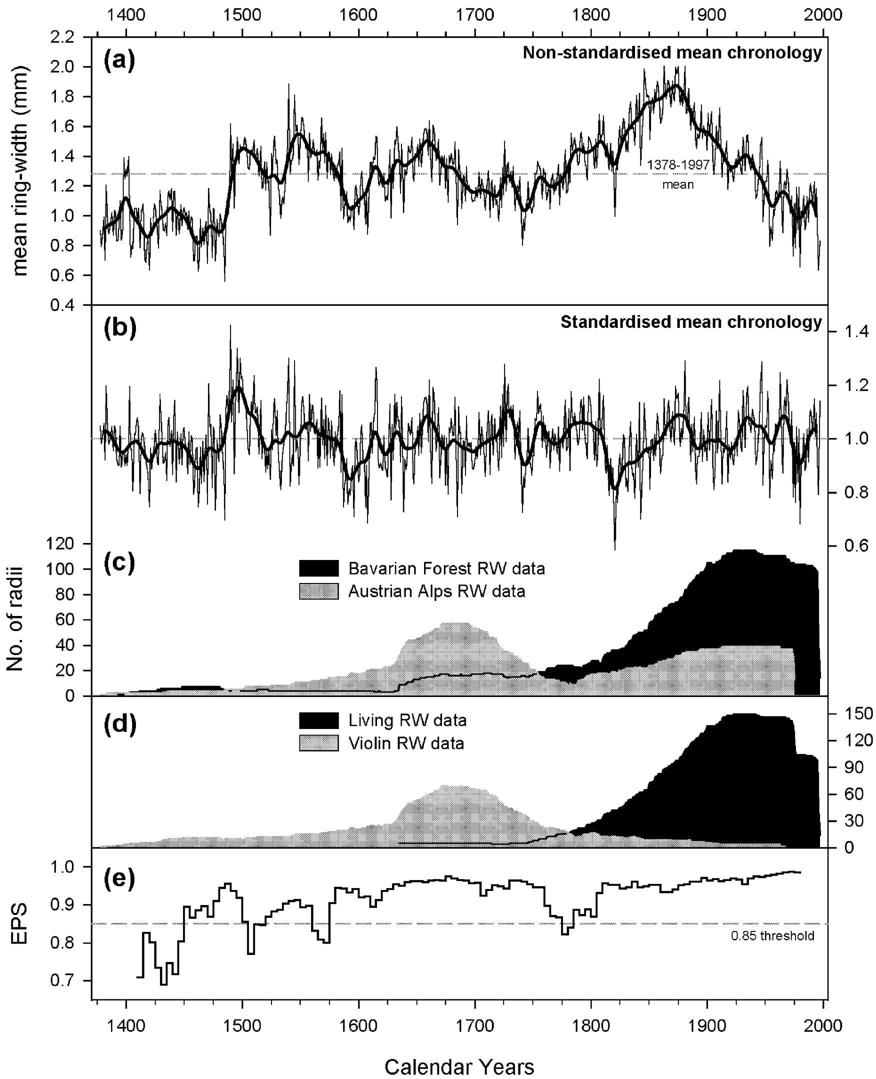

Fig. 6. Characteristics of the BACC Chronology: (**a**) Non-standardised BACC (**b**) Standardised BACC. (**c**) Series replication delineated by region. i.e Bavarian Forest = BAV and Group1; Austrian Alps = AUS and Group 2. (**d**) Series replication delineated by data type. i.e living versus violin (**e**) Running 30 year (lagged by five years) EPS plot for the standardised composite chronology

signal, the relatively strong common signal between the historic violin RW data and the living RW data through the overlap period (Fig. 5), provide sufficient evidence that the data can be combined to develop a regional living/historic composite spruce chronology. This series is referred to as the Bavarian Forest/Austrian Alps living/historic composite chronology or BACC. The OBH data (Table 1) were not included in the development of BACC as we are assessing the validity of using the violin historic TR data for dendroclimatic purposes. However, the high replication of the OBH data in the 15th and 16th centuries (Fig. 2) would undoubtedly extend the length of the regional composite chronology. Figure 6 presents both the non-standardised (a) and standardised (b) composite series for BACC. The former is presented to provide an idea of how much potential low frequency trend might have been removed when the Hugershoff function is used to detrend the RW data to develop the standardised chronology (Fig. 6b).

Undoubtedly the trends of the non-standardised series (Fig. 6a) are a mix of both long-term climatic and biological related trends. The peak in RW values in the late 19th century is related to the wide RW values of young living trees, although chronologies of long lived *Pinus cembra* in the central Alps also show above average RW index values for this period (Nicolussi and Patzelt, 1996). Between 1500 and 1800, however, the lower frequency trends observed in the non-standardised chronology are probably not seriously biased by biological trends in the individual raw RW series as their start and end dates are more randomly dispersed through time compared to the living data. Periods of relatively low productivity are observed around 1600 and from 1690–1760. These periods broadly agree with periods of low index values of *Pinus cembra* in the central Alps (Nicolussi and Patzelt, 1996). The 15th century also shows below average RW values but the low sample replication (Fig. 6c, d) and weak signal strength (Fig. 6e) suggest trends in this period should be interpreted with caution.

The low mean RW values of the 1690–1760 period are not present in the standardised series (Fig. 6b). This highlights the potential for biased removal of lower frequency trends through traditional standardisation procedures like the Hugershoff function. However, low index values are still apparent around 1600 and there is a noticeable period of low index values from 1805–1850. The latter period has been reconstructed as one of the last cool pulses of the "Little Ice Age" in central Europe (Bednarz, 1984; Briffa et al., 2001) and coincides with a period of large scale glacial advance in the Alpine region (LaMarche and Fritts, 1971; Nicolussi and Patzelt, 1996). It seems likely, therefore, that despite coming from trees that probably grew a few hundred meters below tree-line, the BACC series represents a proxy record that portrays past temperature variability.

6. Growth/climate correlations

Using simple correlation analysis, the standardised BACC series (Fig. 6b) was compared to a large scale mean gridded temperature series for a $5° \times 5°$ grid square (Fig. 1) that represents the region containing the Bavarian Forest and Austrian Alps (Jones, 1994; Parker et al., 1995; Nicholls et al., 1995). A standard 17-month period from May of the previous year to September of the growth year was utilised for the analysis which allows the assessment of the influence of previous and present year's temperature on current year's growth. The analysis was undertaken over the period 1856–1950 to eliminate possible anthropogenic influences on spruce growth in recent decades (Eckstein and Sass, 1989; Elling, 1990; Sander et al., 1995). This analysis (Fig. 7a) clearly shows that June/July mean temperatures of the growth year are the dominant control upon high elevation spruce growth. These results agree well with Briffa et al. (2002) who show that the predominant signal in conifer RW chronologies from the Northern Hemisphere is either June/July or June–August temperatures.

Figure 7b compares normalised series of BACC and mean June/July temperatures. The correlation between the series over their common period is 0.45. Although this value is relatively low, the RW data do faithfully follow the lower frequency trends in the climate data. There also appears to be no suggestion over the last few decades for a divergence between the RW data and mean temperatures that has been noted in many regions of the northern Hemisphere (Jacoby and D'Arrigo, 1995; Briffa et al.,

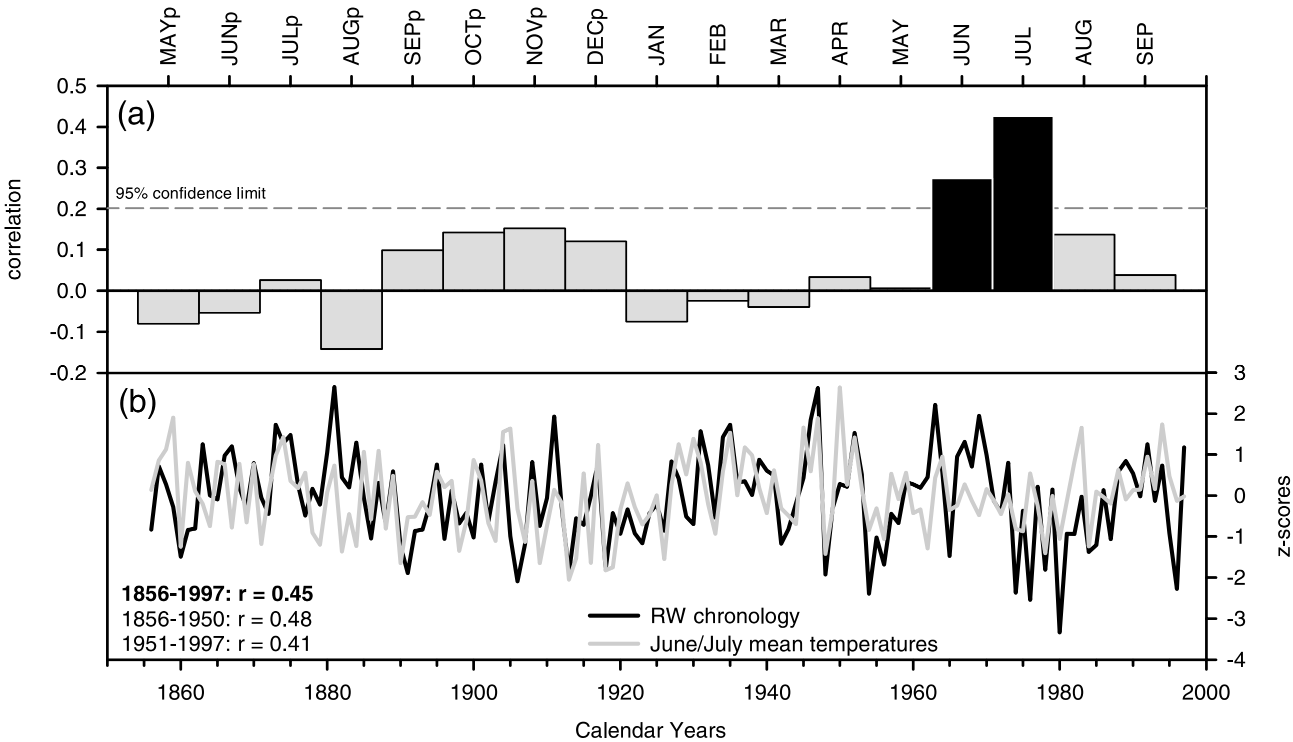

Fig. 7. Calibration of the BACC chronology: (**a**) Correlations between BACC and monthly mean temperatures for the 1856–1950 period. Significant correlations (95% confidence limit) are highlighted in black. (**b**) Comparison between normalised series of the composite spruce chronology and mean June/July temperatures. The series were normalised over the 1856–1950 period

1998a, b; Vaganov et al., 1999; Barber et al., 2000; Lloyd and Fastie, 2002; Wilson and Luckman, 2003). The correlations between both series appear reasonably time stable when calculated over the independent periods 1856–1950 and 1951–1997 (Fig. 7b) indicating that there is no significant weakening of the climate signal due to recent anthropogenic forcing.

The correlations presented in Fig. 7 may be relatively weak because, (1) the living data are essentially biased to the Bavarian Forest (Fig. 6c) and the correlations could improve if other high elevation chronologies from within the grid box (Fig. 1) were included; (2) the BAV and AUS living data were not specifically sampled for dendroclimatic purposes. Wilson and Hopfmueller (2001) point out that the mountain summits of the area they sampled are 100–200 m below the theoretical elevation for tree-line at that latitude (Körner, 1998; Elling pers comm., 2000); (3) following on from the previous point, present day tree-line may not represent the 'true' tree-line and may in fact be depressed down slope due to human activities (Körner, 1998). If this is the case, then most chronologies sampled from the present tree-line may not actually portray as strong a climate signal as would be found in environments where the tree-line is solely controlled by climate. It should also be noted that, in general, RW data portray a weaker temperature signal compared to maximum density data (Briffa et al., 2002). Nevertheless, as maximum density data could never be measured from string instruments, we believe that the "violin" RW data utilised in BACC provide a valid proxy for June/July mean temperatures, especially at decadal and lower frequencies.

7. Comparison to other proxy reconstructions

Several proxies of past temperature, utilising different types of palaeoclimate data, exist for central Europe. For comparative purposes, we have chosen a variety of proxies that are both reasonably specific to the Alpine region and portray a signal that is related to temperature variability.

These data are, (1) a TR reconstruction, utilising RW data of *Pinus cembra*, of June–August mean temperatures for the central Eastern Alps (Nicolussi and Schiessling, 2001); (2) the record of glacial advance from Gepatschferner Glacier (the second largest glacier in Austria), compiled from dendrochronological dating of sub-fossil material and the study of historical paintings (Nicolussi and Patzelt, 1996) and (3) the CLIMHIST (Pfister, 1995) June/July mean temperature index for Switzerland derived mainly from documentary sources.

Although these reconstructions portray slightly different regions and seasonal temperature windows, examination of Fig. 8 clearly suggests a strong common signal between these proxy records. The Nicolussi and Schiessling (2001) temperature reconstruction shows remarkable similarities with BACC at decadal scales, with common cool periods at 1450–1475, around 1600 and 1805–1850. Although the standardised BACC series does not show cool conditions in the early 18th century, relatively low mean RW values are observed over this period in the non-standardised chronology (Fig. 6a), again suggesting that the standardisation procedure has removed some longer term variability. The major difference between BACC and the Nicolussi and Schiessling (2001) temperature reconstruction is in the 20th century, where the central Eastern Alps proxy shows increasing temperatures through the 20th century that are not apparent

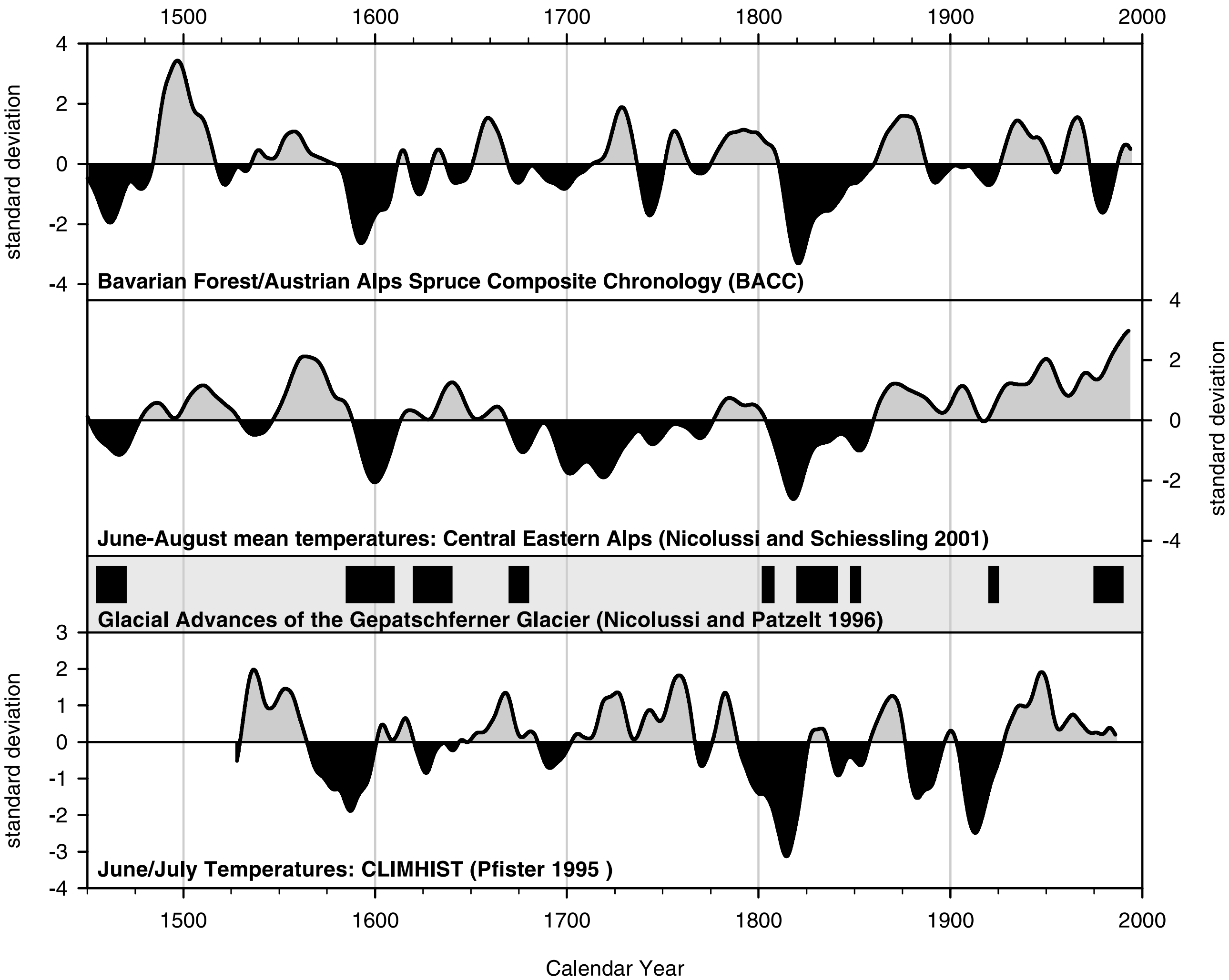

Fig. 8. Comparison of low pass filtered temperature reconstructions. The series were smoothed with a 20 year cubic smoothing spline, and after removing 3 annual values from either end of the smoothed series to reduce end effects, the series were normalised over their 1607–1978 common period. The grey highlighted panel shows periods of glacial advance of the Gepatschferner Glacier (Nicolussi and Patzelt, 1996)

in BACC. Nicolussi and Schiessling (2001) standardised their RW data using the regional curve standardisation (RCS) method (Mitchell, 1967; Cook et al., 1995; Briffa et al., 1996; Esper et al., in press) which attempts to capture more low frequency information than more traditional standardisation methods. The RCS method was not utilised in this study because of insufficient replication in the violin historical TR data. Nicolussi et al. (1995) also suggest that CO_2 fertilisation may also be a factor that may, in part, have caused the observed 20th century increase in productivity of *Pinus cembra*.

The advances of the Gepatschferner glacier (Fig. 8) occur almost synchronously with periods of below average index values in BACC. Only in the mid 18th century do our data suggest cooler summer conditions without a synchronous advance of the glacier. The CLIMHIST data also show strong decadal similarities with BACC, although both our data and the Nicolussi and Schiessling (2001) record appear to lag slightly behind the documentary index. The CLIMHIST data portray the trend to cooler conditions ca. 20 years before BACC for the two main cooler 'pulses' at the end of the 16th century and first half of the 18th century. The reason for this apparent lagged difference is not known. However, the correlation between the unfiltered series of BACC and CLIMHIST is 0.43 over the period 1603–1980 which indicates that there is a reasonably strong common year-to-year signal.

In summary, the BACC record shows similar decadal scale patterns to other temperature proxies from the Alpine region which indicates that the violin data are a potentially useful source of palaeoclimate information. The records shown in Fig. 8 present a coherent general picture of summer temperature conditions over the last 550 years. Cool conditions dominated over the periods ca. 1450–1475, 1575–1650 and 1800–1850 while warmer periods occurred around 1500, the mid 16th century, and for prolonged decadal periods in the 18th and mid 20th centuries.

8. Conclusion

The development of regional proxy temperature series over the past millennium are of pressing importance, not only to allow the study of longer term climate variability, but also to place the 20th century climate in a longer-term context (Mann et al., 1999; Briffa, 2000; Esper et al., 2002). We have shown that RW data measured from string instruments provide a unique source for high elevation TR material from central Europe. The "violin" RW historical data presented in this paper compare well with living high elevation spruce chronologies in the Bavarian Forest and Austrian Alps. More significantly, a composite RW chronology using these data (BACC) shows strong similarities with a TR based temperature reconstruction for the central Eastern Alps (Nicolussi and Schiessling, 2001), documentary records of past temperature in Switzerland (Pfister, 1995) and glacial records from the Austrian Alps (Nicolussi and Patzelt, 1996).

Although this study is explorative, the results are encouraging. We believe that the use of the remaining series in the violin data-base has considerable potential to enhance the results presented in this paper. Continuing analysis using the remaining violin historical TR data-set shows that other high elevation spatial groupings can be identified around the Alpine region (e.g. northern Italy and Switzerland). We hope, from further analysis, to develop a network of regional living/historic composite chronologies for the whole Alpine region. Such a database may allow the identification of the source locations of wood used for instrument making and, most importantly, would be an invaluable data-set to assess climate variability in the Alpine region at a variety of both temporal and spatial scales.

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