Spatial reconstruction of summer temperatures in Central Europe for the last 500 years using annually resolved proxy records: problems and opportunities

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Most palaeoclimate studies in Central Europe, utilizing annually resolved proxies such as tree-ring and documentary sources to reconstruct past temperatures, have focused mainly upon single sites or regional studies. The combined information of published summer temperature reconstructions from the Alpine region show a generally coherent picture of cool conditions for the periods *c.* 1450–1475, 1575–1610, 1660–1710, 1800–1850 and 1875–1925. These reconstructed cool periods can be partly explained by external forcing (e.g. low solar activity and volcanic events). However, these reconstructions, in their present form, cannot be used to comparatively assess spatial summer temperature variability through the region due to methodological differences in their development and the fact that many of them were not originally developed to emphasize spatial patterns. We propose that a network of tree-ring chronologies which have been processed in a consistent way would allow the robust reconstruction of spatial summer temperature variability for high elevations in Central Europe. Unfortunately, most living tree-ring chronologies only go back into the 18th century – so restricting the length of reconstruction. As a possible solution, we introduce a historical database of ring-width series, measured from string instruments, that could be used to extend high elevation spruce chronologies in Central Europe back for at least 500 years.

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Over the past three decades, the Alpine region of Central Europe has been the focus of many palaeoclimate studies to reconstruct past temperatures using high resolution annually resolved proxies such as tree-ring and documentary sources (e.g. LaMarche & Fritts 1971; Schweingruber *et al.* 1978; Eckstein & Aniol 1981; Briffa *et al.* 1988; Pfister 1995; Nicolussi & Schiessling 2001; Wilson & Topham 2004; Luterbacher *et al.* 2004; Frank & Esper in press; Büntgen *et al.* in press; Casty *et al.* in press). Central Europe is unique for palaeoclimate research in that several long (>150 years), high-quality meteorological records (Böhm *et al.* 2001) are available to calibrate and verify palaeoclimate proxies. The Alpine region is specifically important as it incorporates a 'climate divide' between Atlantic, continental and Mediterranean influences that result in a varying spatial signal of temperature over the region (Wanner *et al.* 1997). One of the key aims of the European palaeoclimate community, therefore, is not only to reconstruct climate using single local proxies, but also to develop a spatial reconstruction of climate variability through time. This aim has led to great emphasis on multi-proxy studies due to differences in seasonal response and geographical coverage of the various proxy types (Mann *et al.* 2000; Pauling *et al.* 2003; Luterbacher *et al.* 2004).

This article describes and compares several summer temperature proxy reconstructions for the Alpine region of Central Europe and highlights periods of synchronous reconstructed warm and cold periods between the records. Although these records can be combined to provide a reasonably coherent picture of past summer temperature variability for high elevations in Central Europe, we indicate that these data, in their present form, are not ideal for exploring spatial summer temperature variability through the region due to differences related to (1) the development of the proxy series themselves (i.e. differences between data types (e.g. tree-ring and documentary), processing methods and reconstructed seasons), and (2) the fact that these reconstructions are local or regional in extent and were mostly never developed to emphasize spatial patterns. We detail the limitations of these temperature proxies and propose an ideal scenario that should be sought when aiming to reconstruct spatial climate variability. We conclude by introducing a proxy data set, utilizing ring-width series measured

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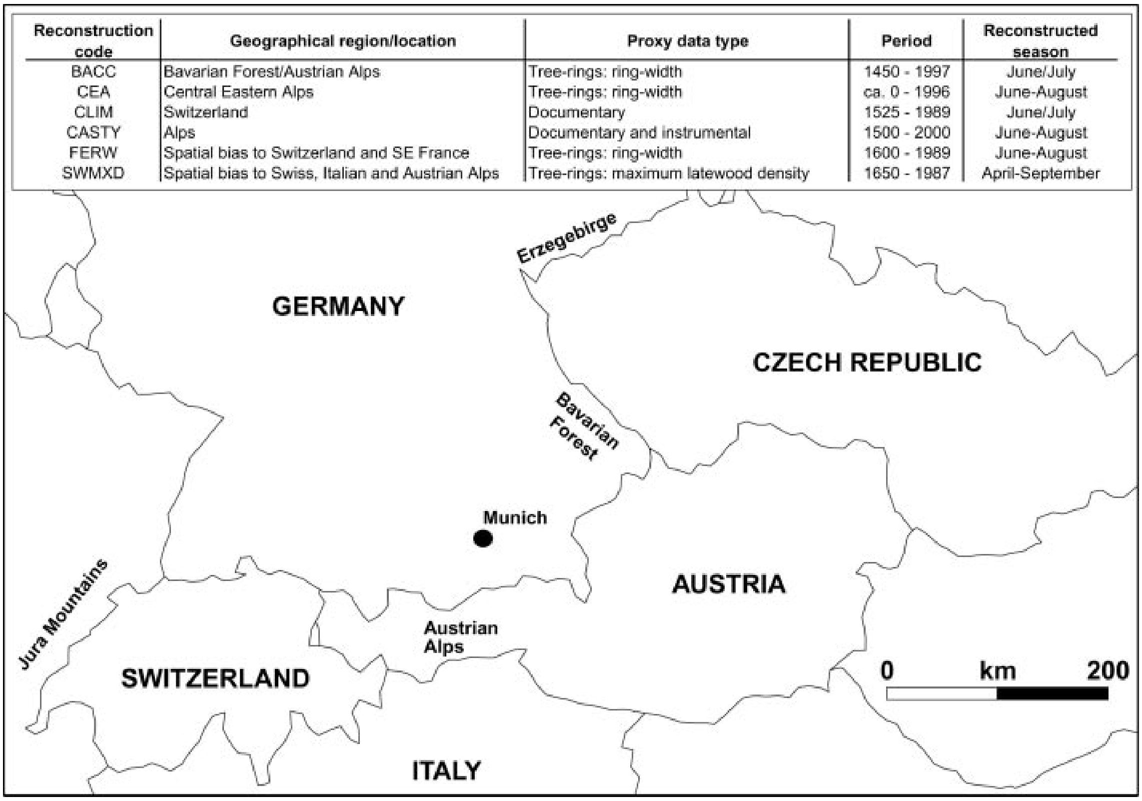
from string instruments, that may be used to develop a consistent spatially resolvable network of summer temperature sensitive chronologies for high elevations in Central Europe for at least the last 500 years.

Proxy data and large-scale coherence

Figure 1 details information and general locations of six annually resolved summer temperature proxies for the Alpine region of Central Europe. The Bavarian Forest/Austrian Alps composite series (BACC) was derived by combining ring-width data from high elevation living *Picea abies* (hereafter PCAB) trees in the Bavarian Forest (1200–1420 m a.s.l.) and Austrian Alps (1850–2000 m a.s.l.) with ring-width series measured from string instruments. The data derived from string instruments were identified to portray the same signal (June–July mean temperatures; Wilson & Topham 2004) as the high elevation living PCAB chronologies by comparison of statistical quality and cross-correlation analysis (see Wilson *et al*. (2004) for method). The Central Eastern Alps (CEA) reconstruction was developed by combining living and subfossil ring-width data for *Pinus cembra* (hereafter PICE) and through correlation analysis was identified to portray June–August temperatures (Nicolussi & Schiessling 2001). The CLIMHIST (Pfister 1995) temperature index for Switzerland was derived predominantly from documentary evidence (scientific writings, narratives, monastery records, warm and cold spells, phenological information, freezing of water bodies, etc.; Pfister 1999). For comparison, we present the June–July season of these data (CLIM). A new reconstruction of summer alpine temperatures based on documentary evidence and early instrumental data back to 1500 is also presented (Casty *et al*. in press). These data represent a regional average for the greater Alpine region developed from a network of spatial gridded (0.5°×0.5°) reconstructions. Frank & Esper (in press) utilized ring-width and maximum latewood density data from a network of high elevation sites distributed across the European Alps to reconstruct regional temperatures. Their network integrated 53 ring-width and 31 density chronologies from four species all above 1500 m a.s.l. A common temperature signal over the study region allowed regional reconstructions to be developed for mean June–August (FERW: 1600–1989) and mean April–September (FEMXD: 1650–1987) temperatures from ring-width (RW) and density (MXD) records, respectively, using nested principal component regression models.



Reconstruction code	Geographical region/location	Proxy data type	Period	Reconstructed season
BACC	Bavarian Forest/Austrian Alps	Tree-rings: ring-width	1450 - 1997	June/July
CEA	Central Eastern Alps	Tree-rings: ring-width	ca. 0 - 1996	June-August
CLIM	Switzerland	Documentary	1525 - 1989	June/July
CASTY	Alps	Documentary and instrumental	1500 - 2000	June-August
FERW	Spatial bias to Switzerland and SE France	Tree-rings: ring-width	1600 - 1989	June-August
SWMXD	Spatial bias to Swiss, Italian and Austrian Alps	Tree-rings: maximum latewood density	1650 - 1987	April-September

Fig. 1. Proxy data information and location. The mean temperature data from Munich were extracted from the Global Historical Climate Network database Version 1 (Vose *et al*. 1992) and have been corrected for inhomogeneities and missing values (Peterson & Easterling 1994).

Figure 2 compares lowpass-filtered versions of the summer temperature reconstructions located in the Alpine region (Fig. 1). Clearly, at multi-decadal scales there is a reasonably strong common signal between these proxy records. In general, the combined information from these series shows that over the Alpine region cool conditions are reconstructed for the periods *c.* 1450–1475, 1575–1610, 1660–1710, 1800–1850 and 1875–1925, which have been shown to coincide closely with periods of glacial advance of the Gepatschferner (GEP) Glacier in Austria (Nicolussi & Patzelt 1996; Wilson & Topham 2004), although it should be noted that glacial advance may not be controlled by summer temperatures alone (e.g. changes in winter precipitation are non-negligible) and differing periods of advance are noted for other Alpine glaciers

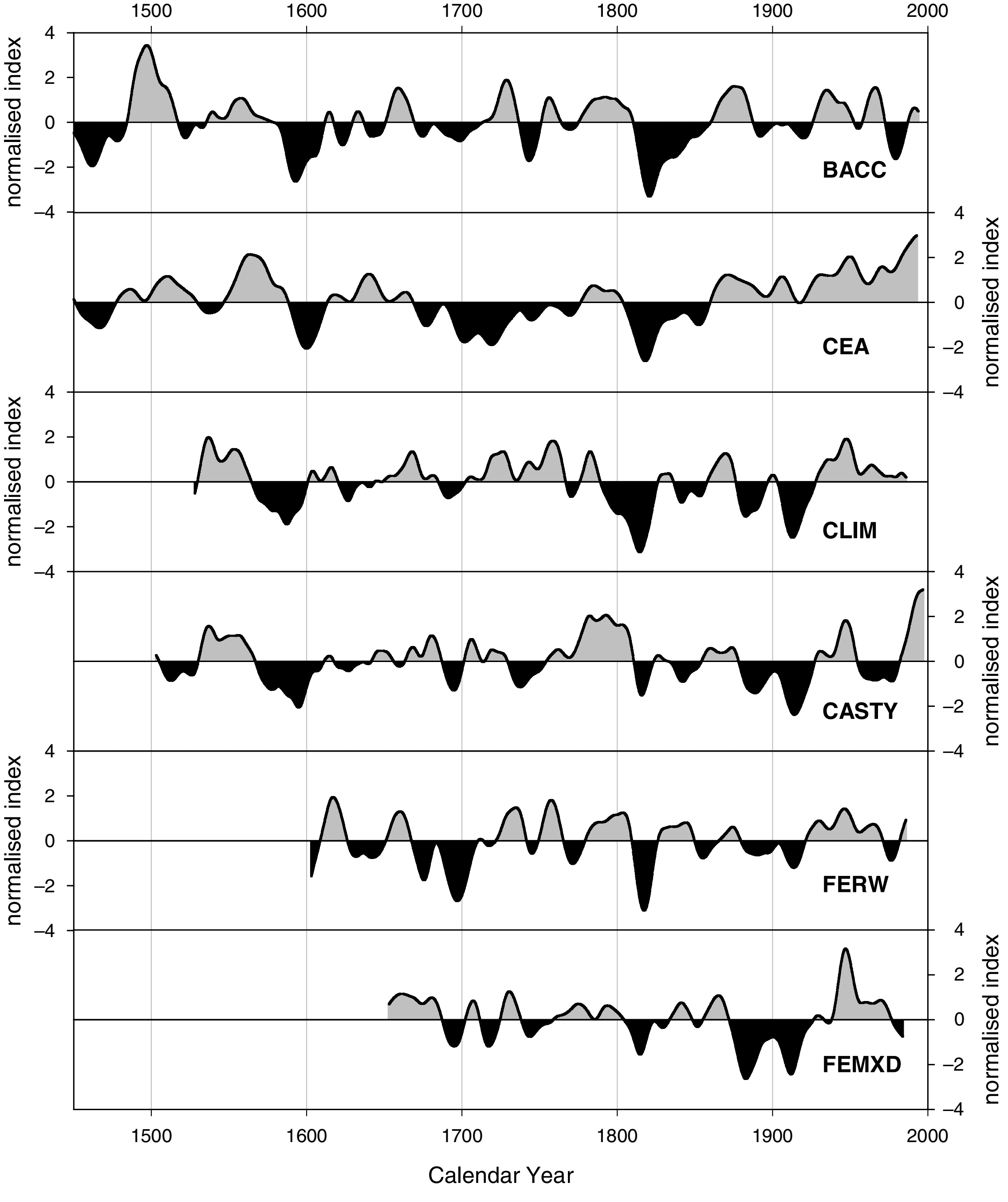


Fig. 2. Lowpass-filtered (20-year cubic smoothing spline) summer temperature reconstructions for the Alpine region. The time series were normalized to their common period after smoothing. The series codes are described in Fig. 1.

(Holzhauser & Zumbühl 1999; Wanner *et al*. 2000). The reconstructions indicate warmer periods around 1500, the mid-16th century, and for prolonged periods in the 18th and mid-20th centuries. Only the CEA and CASTY series show late 20th-century temperatures to be warmer than any other period over the past 500 years.

The temperature variability prior to the mid-19th century, inferred from the different summer temperature reconstructions for the Alps (Fig. 2), is a result of natural forcing (e.g. solar and volcanic forcing) and/or the internal interaction of ocean-atmosphere dynamics. It is also becoming more apparent that recent climate change is further forced by anthropogenic effects (e.g. greenhouse gases, aerosols, etc.; Jones & Mann 2004). In light of natural forcing, therefore, certain periods of common coherence between the reconstructions (Fig. 2) can be partly explained by external factors to the climate system. For example, the 1810–1825 period, which is consistently cool in all the reconstruction time series, coincides with a period of low solar irradiance (the Dalton minimum; Stuiver 1961; Bard *et al*. 2000; Beer *et al*. 2000; Bond *et al*. 2001; Robertson *et al*. 2001) and high volcanic activity (e.g. Tambora 1815; Newhall & Self 1982; Briffa *et al*. 1998; Robertson *et al*. 2001).

Reconstructing spatio-temporal summer temperature variability: a cautionary tale

Despite there being obvious synchroneity between the different reconstructions (Fig. 2), which seem, in part, to be related to external forcing, there are differences between the records that require comment and explanation. For example, during the Maunder Minimum (1645–1715), a period of low solar activity and often quoted as being the coldest winter period during the Little Ice Age in Europe (Luterbacher *et al*. 2000), the summer temperature reconstructions presented in Fig. 2 do not show a coherent period of reconstructed cool conditions through the Alpine region. Only the CEA and FERW records show markedly cooler conditions at this time, but even for these records the Maunder Minimum does not stand out as being an extreme cold period when compared over the last five centuries.

The fact that periods of reconstructed cool conditions in Fig. 2 are only weakly correlated with both periods of solar minima and volcanic events suggests that much of the variance in the reconstructions may reflect regional synoptic spatial variations and internal forcing. Ignoring calibration error – which is often >50% – the differences between these reconstructions could reflect real changes in summer temperature variability over space through the Alpine region. However, we feel that a certain degree of caution is required with this interpretation due to differences related to the development of the proxy series themselves.

1. *Data type*: Although each reconstruction models temperature, the seasonal reconstructed variables differ because varying data types were utilized. The BACC and CEA series were generated using ring-width data from one tree species (PCAB and PICE, respectively), whereas the FERW series of Frank & Esper (in press) was developed from a multi-species network for the whole Alpine region. Their FEMXD reconstruction again used a multi-species network but utilized maximum latewood density as the measured parameter. The different tree-ring parameters and also, but generally to a lesser extent, species affect the final reconstructed seasonal window. This is not a problem with the CLIM and CASTY data, as they exist as monthly or seasonal proxy time-series (Pfister 1995; Casty *et al*. in press). It is difficult, however, to assess what proportion of the differences between the reconstructions (Fig. 2) can be accounted for by differing seasonal parameters. For example, the correlation between the June–July (optimal season for BACC) and April–September (optimal season for FEMXD) seasons for mean temperatures from Munich (Fig. 1) is 0.68 ($p<0.000$) over the 1851–1991 period. After smoothing with a 10-year moving average, however, the correlation increases to 0.90 ($p = 0.04$, after the degrees of freedom have been adjusted for autocorrelation in the smoothed time series (Trenberth 1984)). Similar observations could be made for all temperature records throughout Central Europe. Therefore, as there is such strong coherence at decadal scales between different 'summer' seasons of temperature, it appears that the reconstruction of varying summer windows can only partially account for the observed differences between the smoothed reconstructions presented in Fig. 2. Frank & Esper (in press), however, show incongruities between FERW and instrumental station summer temperatures in the low-frequency domain, where the trends tend to better fit those of the early instrumental annual data, perhaps indicating a modulation of growth rates by winter conditions also. If this is the case, differences in decadal and longer term trends between ring-width and maximum density generated reconstructions may therefore reflect differences between summer and annual seasonal trends. A further possible explanation, which has implications for the CASTY and Luterbacher *et al*. (2004) reconstructions, as they incorporate long meteorological records, is that early warm season instrumental records may indicate higher temperatures than actually occurred due to systematic biases in these early period data (Chenoweth 1993; Moberg *et al*. 2003; Esper *et al*. 2005).

2. *Data processing methods*: As raw tree-ring data are a mix of varying signals (i.e. biological age trends, climate forcing and ecological disturbance; Cook 1985), it is standard practise to detrend these low frequency trends (Fritts 1976) to develop time series of

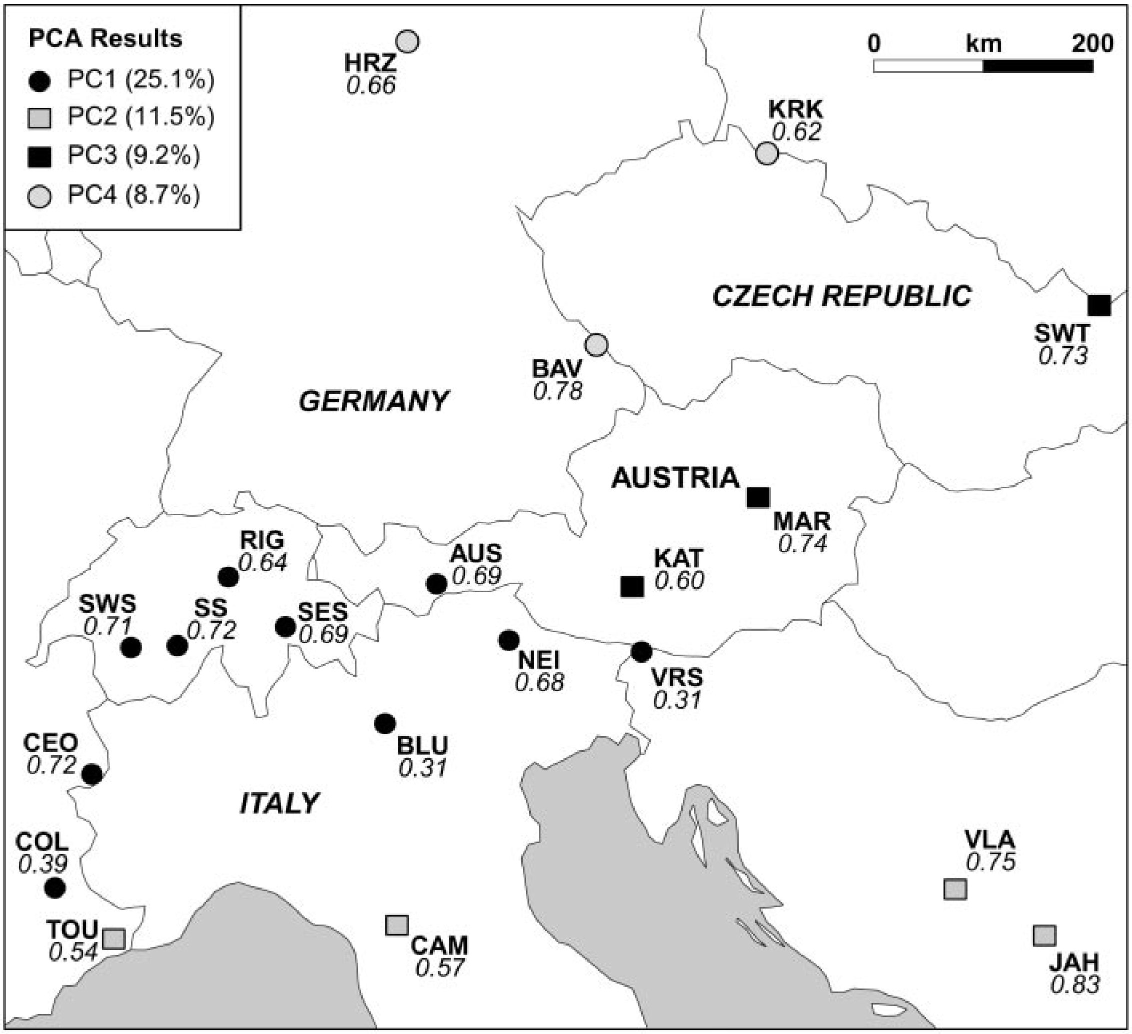


Fig. 3. Principal components analysis results. The PCA was made over the 1850–1974 common well replicated period using chronologies that were standardized using the Hugershoff function (Bräker 1981). Four significant eigenvectors were identified in the PCA. The explained amount of variance of each PC eigenvector is shown in the inset box. The numbers on the map denote the loading of each chronology on the eigenvector on which it most strongly weighs. See Table 1 for description of the chronologies.

unit mean and variance. However, it is difficult, when detrending individual tree-ring series, to remove biologically driven low frequency changes and still retain long-term climatic information. The process of detrending therefore inevitably removes potential long-term climatic information (Cook *et al.* 1995). This is certainly the case for the BACC, FERW and FEMXD reconstructions in Fig. 2 as the tree-ring data used for these series were detrended individually using standard methodologies (Fritts 1976; Bräker 1981; Cook & Peters 1981). However, the tree-ring data utilized in the CEA series were processed using a detrending technique called Regional Curve Standardization (RCS; Briffa *et al.* 1992, 1996; Esper *et al.* 2003). This method aims to capture the long-term variance that is normally removed using traditional, individual series detrending methods. It is possible, for this reason alone, that the CEA record is the only reconstruction that shows increasing temperatures from the 19th century to the late 20th century. With the CLIM and CASTY records, without comparison with independent non-biased reconstructions, it is difficult to assess if they are biased in the frequency domain.

String instruments: a consistent proxy for spatial summer temperature variability in Central Europe

In the previous section, we highlighted problems of using reconstructions that have utilized different proxy types and processing methods for the assessment of spatial summer temperature variability. Without controlling for these factors it is impossible to assess

Table 1. Summary information on the spruce chronologies utilized for the PCA (Fig. 4). 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 are from the International Tree-Ring Data-Bank (http://www.ngdc.noaa.gov/paleo/ftp-treering.html).

Site code	Site name	Elevation (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
SWS	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
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
SWS	South-west Switzerland	1000–1900	982–1986	272
CEO	Mt. Cenis & l'Orgere	1950–2100	1740–1975	29
COL	Col d'Allos	1900	1792–1975	10
TOU	Le Tournairet	2050	1715–1977	26

whether differences between regional reconstructions denote real differences in spatial variability or whether these differences reflect methodological or seasonal biases. Recently, Luterbacher *et al.* (2004) developed gridded spatial reconstructions of monthly and seasonal temperature for Europe using a multi-proxy network. The problems discussed above are relevant to the Luterbacher *et al.* (2004) study, especially prior to the instrumental period, as the different proxy data sets used before this time all vary in their ability to capture long-term climate information.

We propose that a strategy to acquire non-biased information on spatial variability through time is to minimize the effects of the two points discussed in the previous section, i.e. reducing the effects of data type and data processing. Tree-ring data, especially when utilizing only one measured parameter (i.e. ring-width or maximum density), may provide a robust approach to the reconstruction of summer temperature variability across Central Europe. The problem that arises with existing living chronologies in the Alpine region, however, is that the usable length (i.e. the period where the signal-to-noise ratio is high (Wigley *et al.* 1984)) of some of the series is relatively short. Briffa *et al.* (1988) developed spatial reconstructions of summer temperatures for Europe using maximum density chronologies, but the final reconstructions only extended back to 1750. Therefore, extension of the living chronologies is required using either subfossil or historical tree-ring data. However, in most situations this is difficult due to the lack of preserved woody material (Wilson *et al.* 2004).

One potentially useful data set to address this problem is to utilize the tree-ring data set described by Wilson & Topham (2004). They showed that ring-width series measured from violins (and other string instruments) could be used as a proxy data-source for high-elevation summer temperatures in Central Europe. Presently, the violin data set consists of *c.* 2500 measured series, most of which are PCAB, that express the same signal as living PCAB chronologies from high elevations in Central Europe. Although most of the series appear to come from the Alpine region (Topham & McCormick 2000), where the common signal is relatively homogeneous (Böhm *et al.* 2001), we have been able to specifically identify subgroups that come from the western Austrian Alps and Bavarian Forest (Fig. 1; Wilson & Topham 2004). Ongoing analysis has also identified other subgroups for the Erzegebirge Mountains, the Italian Alps, the Swiss Alps and Jura Mountains (see Fig. 1).

To further highlight the potential of identifying distinct variance modes (i.e. regional groups with different signals) from a network of high elevation PCAB chronologies in Central Europe a principal components analysis was undertaken. Figure 3 presents the spatial loadings of 20 high-elevation living PCAB chronologies from Central Europe from a rotated (Varimax; Richman

1986) principal components analysis made over the period 1850–1974. Using the 'scree' method (Cattel 1966), four significant principal components were identified. PC1 clearly shows the dominant mode of variance of high-elevation PCAB trees in the Alpine region, although this signal weakens into southern France and Northern Italy. PC2 expresses the variability of PCAB trees influenced by the Mediterranean although it is biased spatially to the Balkans. PC3 reflects PCAB trees from the southern Czech Republic and Central/Eastern Austria, while PC4 portrays a Central European continental influence upon PCAB tree growth and covers a large area from SE Germany to northern Germany and across to the NE sector of the Czech Republic.

The principal components analysis shows that at least four distinct regional groupings can be identified in the living PCAB data set. The living PCAB data for the Bavarian Forest and Austrian Alps have been extended back, using violin ring-width series, to 1393 and 1378, respectively (Wilson & Topham 2004). It is likely that the broad regional groups identified in the principal components analysis could also be extended back to at least 1500 using this unique data set.

The violin tree-ring data set, however, still does not represent the true ideal scenario from which unbiased spatial reconstructions of temperature can be developed for all seasonal parameters. First, the provenancing of the historic material is difficult to quantify, especially in the period where no living reference chronologies exist. Careful bridging and comparison of statistical properties will have to be made between series, because the regional data sets are extended back in time (Wilson *et al.* 2004; Wilson & Topham 2004). Second, for reasons discussed above due to detrending methods, it will be difficult to resolve long-term variability in these data at periods greater than centennial scales. Experimentation using the RCS method (Briffa *et al.* 1992, 1996; Esper *et al.* 2003) has resulted in unsatisfactory results, and long-term trends observed in PICE chronologies (e.g. CEA, Fig. 2) have not been captured from PCAB data. Finally, the reconstructed season will be restricted to the summer season only (June–July or June–August) and no information about winter temperatures will be extracted. Despite these shortcomings, however, a consistent set of techniques can be applied to this single-species data set to yield an extension of the living PCAB chronologies back to at least 1500. Seasonal response, measured parameter, and methodological differences will be minimized with this homogeneous data set, and therefore noted differences over the spatial network will more likely be related to real spatial differences in signal.

Conclusions

Current annually resolved reconstructions of summer temperatures for Central Europe and the Alpine region provide a reasonably coherent picture of summer temperature variability for the last 300–500 years. Some of this common variability is a result of external forcing from changes in solar and/or volcanic activity. However, it is not clear to what extent differences between the reconstructions represent (1) real spatial trends in climate variability, (2) varying seasonal windows portrayed by the differing proxy types, (3) differences in the methods used to process them, or (4) variance reflecting non-climatic (i.e. temperature) noise.

We propose that a highly replicated ring-width data set, measured from string instruments, originally introduced by Wilson & Topham (2004) for their utilization in dendroclimatology, is a unique spatial network of data that could provide a consistent baseline from which spatial information of summer temperatures for high elevations in Central Europe could be extracted. We hypothesize that the development of a spatial network of living/historical composite PCAB chronologies would not only allow identification of the general source locations of wood used for instrument-making, it would also be an invaluable data set by which to assess summer temperature variability from high elevations in Central Europe at a variety of both temporal and spatial scales.

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