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Five centuries of Central European temperature extremes reconstructed from tree-ring density and documentary evidence

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ABSTRACT

Future climate change will likely influence the frequency and intensity of weather extremes. As such events are by definition rare, long records are required to understand their characteristics, drivers, and consequences on ecology and society. Herein we provide a unique perspective on regional-scale temperature extremes over the past millennium, using three tree-ring maximum latewood density (MXD) chronologies from higher elevations in the European Alps. We verify the tree-ring-based extremes using documentary evidences from Switzerland, the Czech Republic, and Central Europe that allowed the identification of 44 summer extremes over the 1550–2003 period. These events include cold temperatures in 1579, 1628, 1675, and 1816, as well as warm ones in 1811 and 2003. Prior to 1550, we provide new evidence for cold (e.g., 1068 and 1258) and warm (e.g., 1333) summers derived from the combined MXD records and thus help to characterize high-frequency temperature variability during medieval times. Spatial coherence of the reconstructed extremes is found over Switzerland, with most signatures even extending across Central Europe. We discuss potential limitations of the tree-ring and documentary archives, including the (*i*) ability of MXD to particularly capture extremely warm temperatures, (*ii*) methodological identification and relative definition of extremes, and (*iii*) placement of those events in the millennium-long context of low-frequency climate change.

1. Introduction

Meteorological extremes are of importance to the state, functioning, and stability of ecosystems and societies (IPCC, 2007 and references therein), and are as such of interest to researchers, policy makers, and the media (Meehl et al., 2000). Awareness to extreme events is intermittently piqued by the unwelcome surprises that such events bring, refreshing the knowledge that, despite modern technologies, societies remain vulnerable to shorter-term climate anomalies (Allison et al., 2009). The 2003 heat wave (Beniston, 2004; Luterbacher et al., 2004; Rebetez, 2004; Schär et al., 2004), the 1999 wind storm (Ulbrich et al., 2000; Goyette et al., 2003), and the disastrous flood events of the 1990s–2000s all around Europe (Kundzewicz et al., 1999; Christensen and Christensen, 2003; Brázdil et al., 2006) are examples of recent extremes with consequences on ecological systems and local to sub-continental economic activity.

A number of investigations have analyzed long-term trends in climatic extremes and their potential relationships to on-going and projected global warming (Groisman et al., 1999; Karl and Easterling, 1999; Solow, 1999; Alexander et al., 2006; Hegerl et al., 2006; Della-Marta et al., 2007). However, the greatest limitation for assessing changes in the frequency of extremes as a function of climatic state is the paucity of data, both in terms of record length and geographical coverage. Despite the fact that systematic instrumental measurements in Europe reach back to the mid 19th century, it remains difficult to statistically determine whether an extreme event falls within the normal range of variability or is truly unusual in magnitude (Schär et al., 2004). From this perspective, proxy data provide a chance to assess variations in extremes over many centuries, including the detection of changes in extremes with respect to the mean climatic state. In addition, the combination of different types of proxy data is a powerful method to increase reconstruction quality and to enable a robust investigation of synoptic variability in the past. Such combined approaches permit capitalizing upon the strengths of proxy records, while simultaneously reducing proxy specific noise. To meet this objective, well-replicated and precisely dated proxy archives of annual or even higher resolution should be developed. Dendrochronological timeseries of tree-ring width (TRW) and maximum latewood density

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(MXD), as well as documentary sources – which can provide information even at sub-daily resolution (Brázdil et al., 2005 and references therein) – uniquely fulfill these requirements.

Herein, we compile three MXD chronologies from the European Alps spanning the past millennium. These chronologies are derived from trees growing near their thermal growth limits where the MXD parameter is known to be a particularly strong recorder of summer temperature variations (e.g., Frank and Esper, 2005; Büntgen et al., 2007). We compare these records with temperature extremes derived from documentary data including precisely dated narrative accounts of climatic anomalies (e.g., cold- and heat waves, droughts and wet spells) and daily extremes (e.g., late and early frosts), as well as calibrated indirect data (e.g., phenological information) (Pfister, 1999; Brazdil et al., 2006). We here aim to (*i*) develop and improve techniques to preserve and detect temporal changes of extreme events in dendrochronological records, (*ii*) develop a calendar of anomalous warm and cold summers back into medieval times, and (*iii*) compare tree-ring and documentary evidence for extreme events. The last point will serve as a basis to verify documentary indices prior to AD 1500 when such data become very sparse. We detail the occurrence of temperature extremes in the context of multi-centennial climate variability and discuss some proxy archive characteristics.

2. Data and methods

2.1. Tree-ring data, detrending and extreme year detection

Three regional-scale datasets of living and historic MXD samples from Lauenen (LAU), the Lötschental (LOE), and Tyrol (TYR) were considered (Fig. 1a). The LAU dataset consists of 206 *Picea abies* samples and covers the 982–1976 period (Schweingruber et al., 1988). The LOE dataset contains 181 *Larix decidua* samples and covers the 735–2004 period (Büntgen et al., 2006a). The TYR dataset (1028–2004) consists of 227 *Picea abies* series (Esper et al., 2007). This data compilation is perhaps unique, as it represents the highest density of millennium-long MXD records in the world. All tree-ring data can be downloaded from the WSL dendro database, Switzerland (www.wsl.ch/dendro). Sample replication of these chronologies is relatively even throughout time (Fig. 1b), and each record contains a strong summer temperature signal. All three MXD chronologies reveal maximum correlations with April–September (AMJJAS) temperature: 0.62 for LAU, 0.64 for LOE, and 0.66 for TYR (all $p<0.01$). In contrast, correlations between TRW and summer temperature are only in the range of 0.36–0.43 (see supplemental Figure S1).

To remove the biological age-trend and facilitate examination of climatic extremes in the context of adjacent years and decades, the MXD data were detrended using a high-pass 30-year cubic smoothing spline filter (Cook and Peters, 1981) (Figure S2). The length of this filter corresponds to the length of a standard climatological period (Guttman, 1989) and roughly equals to the memory period of human individuals recalling climatic extremes (Brázdil et al., 2005). The latter may be relevant for subsequent comparisons with documentary evidence. After normalizing the individual MXD measurement series over their full lengths, values were divided by a 50-year moving window standard deviation (SD) (Figure S3) in order to mitigate artifacts in local variance (Frank et al., 2007a). For each measurement series, years with positive or negative anomalies 1.5 SD above or below average were categorized as extremes. This threshold was selected based on the balance of positive and negative extremes and the total number of years identified amongst trials with 1.0, 1.5, and 2.0 SD thresholds. For each site, the percentage of series indicating negative or positive extremes were tallied, thereby resulting in timeseries of both positive and negative extremes. These positive and negative extreme series were calculated for each site, LAU, LOE, and TYR (Figure S4), and merged towards a single Alpine record. Defining extremes when anomalies exceed 'variable thresholds' (Watson and Luckman, 2001; Frank et al., 2005) is useful because it allows a comparison between extremes occurring in different regions, at different elevations, or from different data sources (Carril et al., 2008).

2.2. Instrumental and documentary data

Instrumental temperature data were derived from the HISTALP database for the Greater Alpine Region (4–19°E and 43–49°N, 0–3500 m a.s.l.). The data include low-elevation station records that are regionally representative and allow calibration over an exceptionally

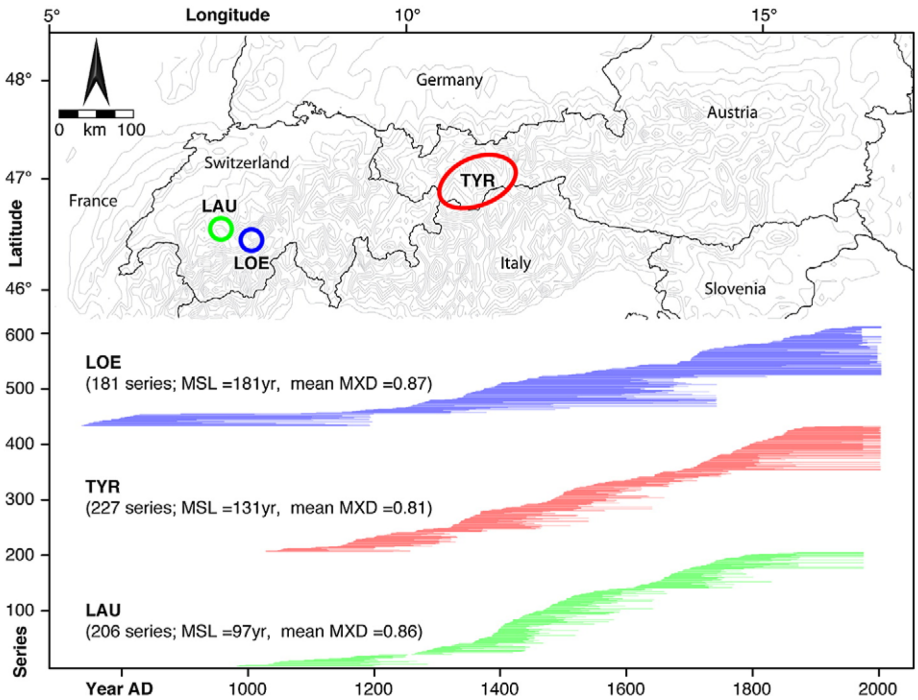

Fig. 1. Map of the three tree-ring chronologies: Lauenen, Lötschental and Tyrol in the central Alps, and their corresponding sample replication during the last millennium.

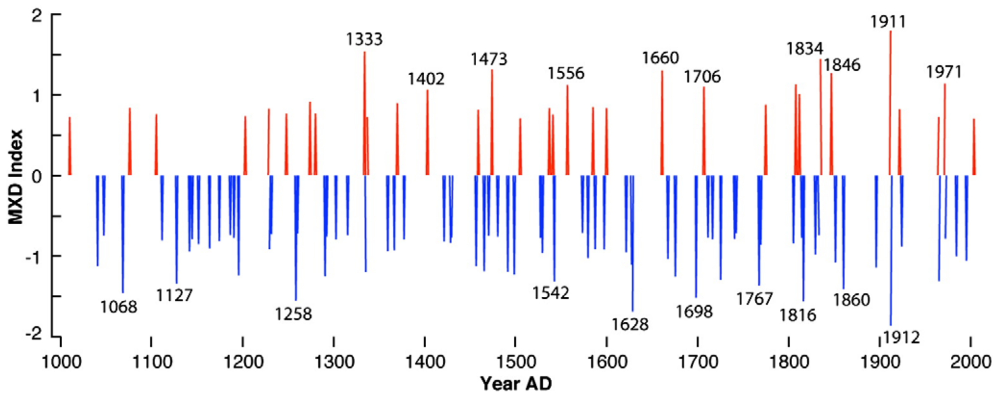

Fig. 2. Alpine-wide MXD-based extreme year record.

long period back to 1774 (Auer et al., 2007). Temperature records were high-pass filtered using 30-year splines to make these data comparable to the high-pass filtered MXD timeseries.

Documentary-based temperature indices from Switzerland (CH; 1550–1816), the Czech Republic (CZ; 1550–1854), and a Central European composite (CE; 1500–1759) were used for comparison with the MXD data. Indices were obtained by transforming various types of documentary sources into weighted temperature indices on an ordinal scale (see e.g., Pfister, 1992; Brázdil et al., 2005; Dobrovolný et al., 2010). Weighted monthly temperature indices were based on a seven-term classification: 3 extremely warm, 2 very warm, 1 warm, 0 normal, −1 cold, −2 very cold, −3 extremely cold. Seasonal and annual indices were obtained by summing the corresponding monthly values. In order to compare the documentary-based extremes with those derived from MXD, data were normalized over their full period, values divided by a 50-year running standard deviation in order to mitigate artifacts in local variance, and high-pass filtered using 30-year splines.

3. Results

3.1. MXD-based extremes

Based upon the application of the 1.5 SD threshold over the common period, 110 extreme summers were identified in LOE, 132 in LAU, and 131 in TYR. Of these, 26 are shared between LOE and LAU, 29 between LOE and TYR, and 57 between LAU and TYR, indicating a higher common variance between LAU and TYR. Over the early, pre-1500 period these values change to 7 (LOE *vs* LAU), 8 (LOE *vs* TYR), and 26 (LAU *vs* TYR), suggesting that the coherence between the three records slightly decreased back in time. Reduced agreement of the identified extremes is in part a consequence of applying a threshold to define extremes and generally provides a pessimistic/conservative view of the common signal. For example, a value exceeding +1.5 SD at TYR is considered to not agree with a value of +1.4 SD at LAU. Comparison of the signs of the different extremes indicated a much stronger coherence, especially between the years with negative extremes. 65% of agreement was found between LOE and LAU extremes (81% between the negative extremes), and 55% between LOE and TYR (63% between the negative extremes). Agreement between the signs of LAU and LOE is 70% (75% between the negative extremes) and 84% between LAU and TYR (86% between the negative extremes). Finally, the agreement between the signs of TYR and LOE is 80% (93% between the negative extremes) and 72% between TYR and LAU (87% between the negative years).

Fig. 2 shows the Alpine composite MXD-based extreme year timeseries derived from averaging the three individual site records. The percentage of positive extremes (32%) is substantially smaller than that of negative ones (68%), and it appears worth noting that before 1195 only negative anomalies were found. Possible biases in the detection of positive *vs* negative anomalies will be discussed below. The more recent extremes coincide with evidence from other sources and direct measurements, including 1816, the so-called 'Year without summer' (Harrington, 1992; Robock, 1994), and 1807, reported as the second warmest summer (after 2003) over the past 500 to 1250 years in the Alps and even in continental Europe (Luterbacher et al., 2004; Casty et al., 2005; Büntgen et al., 2006a). New evidence is provided for earlier temperature extremes during the past millennium (see also Büntgen et al., 2005, 2009), such as the summers of 1068, 1333, and 1542. The negative departures in

Table 1
Extreme warm (red) and cold (blue) summers based upon three MXD chronologies. Validation with instrumental and documentary data for Switzerland (CH), the Czech Republic (CZ) and Central Europe (CE) is indicated by the number of stars depending on the amount of data also showing an extreme summer (beyond the 1.5 SD threshold).

1000-1549 (MXD)				1550-1773 (MXD+DOC)		1774-2000 (MXD+DOC+INS)	
1009	*	1302	*	1556	**	1774	**
1040	*	1315	*	1573	*	1807	**
1047	*	1333	*	1579	****	1811	****
1068	*	1335	*	1584	**	1814	*
1075	*	1336	*	1587	*	1816	****
1104	*	1359	*	1597	*	1829	*
1111	*	1366	*	1599	*	1833	*
1127	*	1369	*	1621	*	1834	***
1141	*	1377	*	1627	*	1846	**
1144	*	1402	*	1628	****	1851	*
1151	*	1421	*	1660	*	1860	**
1163	*	1428	*	1667	***	1896	*
1174	*	1429	*	1675	****	1911	*
1186	*	1456	*	1698	**	1912	*
1190	*	1458	*	1706	**	1921	*
1195	*	1465	*	1711	*	1924	*
1202	*	1470	*	1716	**	1964	*
1228	*	1473	*	1725	**	1965	*
1229	*	1480	*	1740	*	1972	*
1231	*	1491	*	1742	**	1984	*
1247	*	1498	*	1767	*	1995	*
1258	*	1504	*	1769	*	2003	*
1260	*	1527	*				
1273	*	1529	*				
1279	*	1536	*				
1290	*	1540	*				
1292	*	1542	*				

**** MXD+CH+CZ+CE+Inst
*** MXD+CH+CZ+Inst or MXD+CH+CE+Inst or MXD+CZ+CE+Inst
** MXD+CH+Inst or MXD+CZ+Inst or MXD+CE+Inst
* MXD+Inst
**** MXD+CH+CZ+CE
*** MXD+CH+CZ or MXD+CH+CE or MXD+CZ+CE
** MXD+CH or MXD+CZ or MXD+CE
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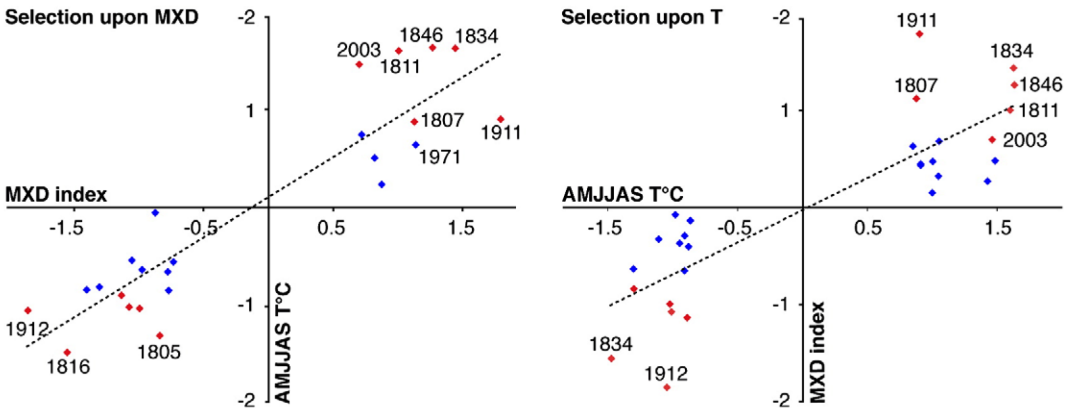

Fig. 3. Cross-validation of the MXD-based extreme years and instrumental data (1774–2003). Red points indicate the common extremes between the two dataset.

1258 (and 1260) provide additional support for significant cooling following an unknown, but likely tropical eruption, with one of largest sulfate peaks in ice-core records during the Holocene (Oppenheimer, 2003) and climatic fingerprints across in the western United States (LaMarche and Hirschbock, 1984), Mongolia (D'Arrigo et al., 2001), and northern Siberia (Hantemirov et al. 2004). A complete list of extremes detected in the Alpine-wide composite MXD dataset is provided in Table 1.

3.2. Validation against instrumental data

To validate the temperature signal of detected extremes in the Alpine MXD data, the composite record is compared with AMJJAS instrumental temperatures (Fig. 3). This was done by selecting the extreme years and plotting the corresponding values for the instrumental data, and *vice-versa*. It is evident that extreme years derived from the MXD data have the same sign and often also a similar magnitude as those derived from instrumental measurements (i.e., 1811, 1846, 1834, 1911, and 2003 for warm and 1805, 1816, and 1911 for cold summers). Similarly, extreme AMJJAS temperatures detected in instrumental data for the period 1774–2003, compared with the MXD values, yielded again a broad correspondence, revealing a two-way consistency between the instrumental and proxy-based extremes. Values close to the *x*-axis are related to extremes detected in one archive but less strongly validated in the other archive. Although the magnitude is occasionally not comparable, without exception, all MXD (instrumental) based extremes were validated by an anomaly of the same sign in the instrumental (MXD) data. Overall, these comparisons help verify the (extreme) temperature signal in the MXD data. Correspondence between extremes identified in the instrumental and MXD data are summarized in Table 1.

3.3. Documentary evidence

To extend the knowledge of extreme summers and conduct cross-proxy validation over longer periods, the MXD data were compared against documentary-based temperature indices considering two seasons (JJA and AMJJAS) and three spatial domains (CH, CZ, and CE). As expected from the climate response of Alpine MXD data (Frank and Esper, 2005; Büntgen et al., 2008a), best agreement was found with the longer AMJJAS period. MXD and documentary derived extreme summers agree in sign in ~90% of the cases. However, the amplitude of documentary-based extremes does not always match the MXD extremes, particularly for warm summers. Correspondence between extremes identified in the documentary and MXD data are summarized in Table 1.

Correlations between the MXD chronologies and AMJJAS instrumental and documentary data for the CH, CZ, and CE regions are shown in Table 2 for the full documentary period back to 1500, the common 1550–1750 documentary period, and the extended instrumental period (1774–2000). The highest correlation of 0.66 is found between the merged MXD and CH documentary data over the 1550–1750 period. Agreement with evidence from CZ ($r=0.43$) and CE (0.45) is, as expected due to the greater distance, lower though still statistically significant. Over this early period, correlations between the individual records and the CH documentary data range from 0.43 to 0.63. Correlations with instrumental data over the 1774–2000 period typically yield higher values.

A more detailed comparison of the positive and negative extremes in the individual MXD records is shown in Fig. 4. MXD and documentary data were plotted on an index scale from +3 to −3, and values corresponding to the 30 most extreme positive and negative summers based upon the documentary data shown. Most evident is the strong coherence between the individual MXD records and the CH documentary extremes, with a number of values approaching +12 or −12 indicating near perfect correspondence among all sources. Comparison of the single MXD records reveals agreement in several cases. There are only a few years where two of the three MXD records show opposite signs compared to the documentary evidence; the origin of this disagreement requires further exploration.

Another question addressed here concerns the match between tree-ring and documentary evidence over the shorter JJA season. This

Table 2
Correlation coefficients between the documentary-based series from Switzerland, the Czech Republic, temperature reconstruction for Central Europe, and the MXD chronologies using the 1550–1816, 1550–1854, and 1550–1759 periods, respectively, as well as the common period 1550–1750. The correlations between MXD and the instrumental data 1774–2000 for Switzerland (HISTALP dataset) and Central Europe (HISTALP dataset and Prague homogenized series) are also reported. All the correlations refer to the season AMJJA.

	Switzerland (CH)		Czech (CZ)		Central Europe (CE)		Instrumental data (1774–2000)	
	1550–1750	1550–1816	1550–1750	1550–1854	1550–1750	1550–1759	CH	CE
Lötschental	0.43	0.46	0.23	0.31	0.30	0.30	0.64	0.51
Lauenen	0.63	0.63	0.40	0.41	0.45	0.45	0.62	0.54
Tyrol	0.50	0.50	0.37	0.40	0.33	0.33	0.64	0.10
Mean	0.66	0.67	0.43	0.46	0.45	0.46	0.72	0.58

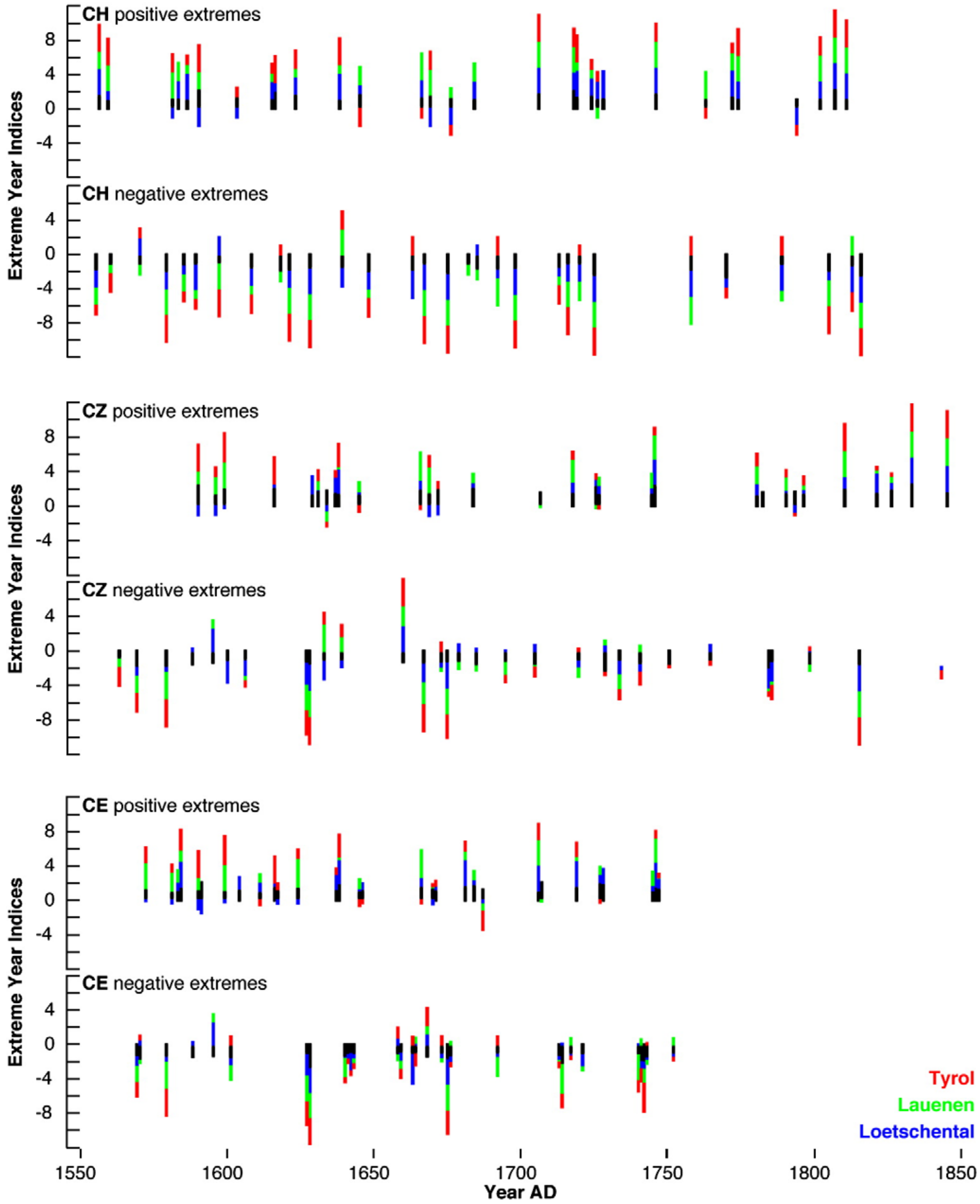

Fig. 4. The 30 most extreme positive and negative summers according to documentary evidence from Switzerland (CH), the Czech Republic (CZ), and Central Europe (CE) compared to the three regional-scale MXD-based chronologies of Tyrol (TYR), Lauenen (LAU), and Lötschental (LOE).

assessment is relevant as early, pre-1500 documentary evidence will likely be restricted to seasonal (not monthly) resolution due to declining data quantity, quality, and precision. To analyze discrepancies that may result from sub-optimal seasons, the MXD data were sorted according to the differences with JJA documentary index data, with large differences indicating years with poor cross-proxy agreement (Table 3). Analysis of the monthly documentary data indicated that years with "cooler" MXD values (e.g., 1552, 1557 and 1659) generally match historical evidence indicating one or more cold months in spring and/or fall. Similarly, several years with "warmer" MXD values (e.g. 1584, 1588 and 1596) match warmer spring and/or autumn months in the documentary data. While not conclusive, these results provide indication for how seasonal differences in proxy archives can lead to biases in reconstructed extremes. Results over the shorter JJA season also serve as an extra-validation of the signal, as the years with greatest discrepancies could easily be explained by "seasonal mismatch".

Table 3
Years in which the difference between JJA index and the MXD record are maximum (left) and minimum (right), with relative observations about monthly temperature conditions based on documentary indices for Switzerland.

Year	Observation	Year	Observation
1552	Cold spring	1584	Warm May, September
1557	Cold March	1588	Warm May, September
1659	Cold September	1596	Warm September
1711	Cold April, September	1598	Warm September
1742	Cold September	1647	Warm autumn
1776	Cold May, September	1657	Warm spring
1777	Cold May, September	1660	Warm spring, September
1837	Cold spring, autumn	1696	Warm May
1851	Cold May, September	1761	Warm autumn
		1762	Warm spring
		1810	Warm September
		1811	Warm spring

3.4. Spatial signature

To explore the spatial domains of the reconstructed temperature extremes, a composite analysis of MXD-based evidence and multi-proxy European-scale gridded June–August (JJA) temperatures (Luterbacher et al., 2004) was performed over the 1700–2002 common period (Fig. 5). Due to the seasonal resolution available, these calculations were again made using JJA data, and as such might be viewed as conservative estimates of the spatial significance of MXD-derived extreme events. Despite this limitation, distinct spatial patterns of positive and negative temperature anomalies (relative to 1901–1995 calibration average) were obtained. The average pattern of the 20 warmest summers showed maximum positive anomalies over Central Europe extending from the western UK to Poland, and from northern Africa to southern Finland. Interestingly, the average spatial anomaly pattern of the 20 coldest summers showed maximum negative anomalies over Western Europe, but with a westward shift of the center of cold and anomalies extending across the UK and Spain. The warm European summer patterns were most likely influenced by more local continental high-pressure conditions, whereas cold summers were associated with increased maritime influences and low-pressure situations.

4. Discussion

Here, we applied a statistical approach to determine the occurrence and frequency of temperature extremes recorded in tree-ring chronologies and compared these findings with evidence from long instrumental records and documentary evidence. By combining information from different proxy records and proxy types, the strength of a climate signal is increased and the range of extractable parameters (such as extremes) most likely also extended. Our approach allowed us to detect 44 extreme years over the 1550–2003 period for which all data sources showed agreement. Several other years were identified in the single series, but they are less coherent between the various archives and can thus not unequivocally be categorized as summer temperature extremes. Documentary data from Switzerland, the Czech Republic, and a composite series for Central Europe served as a framework to understand the degree of coherence between the different proxies. With the objective of developing a framework for evaluation of past extremes, in the following discussion, we focus on the strength of this approach and on the uncertainties of detected extremes as related to the characteristics of the proxy archives. In this way, we critically evaluate the best way to perform multi-proxy approaches and the limitations that need to be understood and overcome.

4.1. Proxy comparison

In case diverse proxies have the same dominant climatic control, the final signal is enhanced by their combination and the results should become more reliable (McCarroll et al., 2003). Thus, the identification of the 44 extreme years back to 1500 AD can be considered a successful and promising result. However, extreme events derived from the various documentary and tree-ring timeseries do not always match. Besides the noise inherent to individual records, this result is not fully surprising, as summer weather patterns in Central Europe are generally of limited spatial extent. Summer temperatures are associated with local radiation-driven weather regimes, whereas winter temperatures patterns are generally associated with larger scale, typically advective synoptic regimes. Indication for limited spatial representation of reconstructed extremes was suggested by the comparisons with CH, CZ, and CE documentary records (see Fig. 5 and Table 2), where coherence appeared to be inversely associated with distance.

Disagreement in the occurrence of extreme years in tree-ring and documentary data, which was observed in some years, could be associated with climatic factors other than summer conditions affecting MXD (Frank et al., 2007b; Büntgen et al., 2008b). Similarly, documentary archives also may indicate the occurrence of extreme intervals such as flooding, heat waves or cold snaps that are short in duration and may not leave obvious fingerprints upon the formation of tree-ring width and density properties.

The MXD measurements showed a greater number of negative than positive extremes. For example, when categorizing summers in the Swiss documentary and instrumental data as extremely warm (1540, 2003, 1536, 1616, 1718, 1947, 1556, 1706, 1724, 1534, 1545, 1603, 1623, 1645, 1669, 1718, 1726, 1728, 1950, 1952, and 1994) (Pfister, 1999), only five of them – namely 1540, 2003, 1536, 1556, and 1706 – stand out in the MXD record (Fig. 2). Some of the warm summers missing in the MXD records, such as 1603, 1616, 1623, 1645, 1669, 1718, 1719, and 1947, were also extremely dry (Pfister, 1992) and appear to not be consistently recorded in the MXD chronologies. These potential limitations of capturing positive extremes could be due to the non-linearities related to wood-anatomical thresholds for positive temperature extremes as well as mixed influences on growth (see below). These characteristics emphasize the importance to consider individual signal and noise components in the proxy archives, and the possibility to reduce potential biases in one archive by (informed) consideration of other proxy types.

Our results also emphasize the importance of seasonality when comparing high-frequency events such as climatic extremes. For

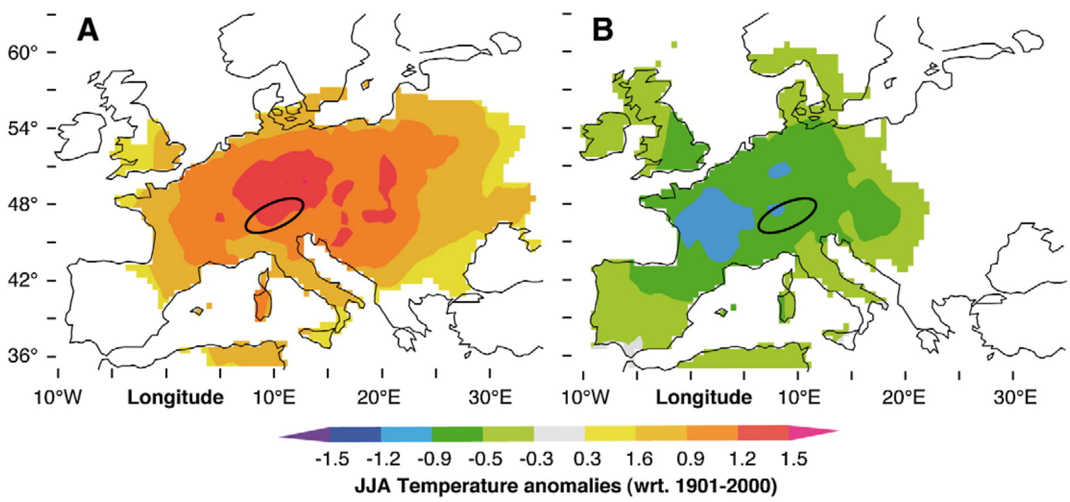

Fig. 5. Average JJA temperature anomalies of (A) the positive and the (B) the negative extreme events over the last three centuries (using the KNMI climate explorer http://climexp.knmi.nl).

example, as efforts are made to quantify medieval climate, the sparse documentary data are likely only sufficient to yield sporadic information on summer temperatures (e.g., JJA) and not monthly resolved information. In addition, it is notoriously difficult to obtain information on autumn in documentary archives. Thus comparisons between documentary sources for the first half of the last millennium and MXD will be particularly challenging. This was illustrated by the analysis of mismatches when only JJA (instead of AMJJAS) data were utilized (Table 3) where the largest discrepancies could be easily explained by spring and/or autumn monthly anomalies. However, it should be mentioned that other discrepancies from the instrumental period (e.g., 1976, 1999, and 2000) cannot be explained by seasonal differences and it is not yet clear if this depends upon biological factors, external forcing, or methodological issues. Seasonal differences in proxy response shows the potential for multi-proxy reconstructions, but also suggests some dangers in combining data with different optimal seasonal windows since the subtle biases in the reconstructed seasonality may be poorly understood.

4.2. Tree-ring uncertainty

In order to quantify the frequency of extreme events, it is important not only to detect single extreme years but also to confirm that these extremes are influenced by temperature and are not site-specific or simply a reflection of some random background noise. Such confirmation is possible when independent datasets show the same signal and also when validation exercises demonstrate the general reliability of a proxy record. In our study, three independent temperature sensitive MXD chronologies from the Alpine region, allowed for the first time, an assessment and confirmation of extreme years over almost the past millennium. Comparison of these records from TYR, LAU and LOE indicated a good agreement and validation exercises showed that the mean of the three datasets was a better indicator of extremes than any particular record alone. Greater disagreement among the MXD records was observed in medieval times.

The reduction in sample size back in time, characteristic for most proxy records, possibly contributed to poorer agreement towards the early portion of the records. In addition, less obvious but potentially more important problems are related to the fact that the historical samples were derived from construction timbers, and likely do not represent a few homogeneous forest stands. The exact provenance of the wood remains, however, less certain (Wilson et al., 2004; Büntgen et al., 2005, 2006b) in comparison to the living trees that constitute the more recent portion of the chronologies. Nevertheless, it can be assumed that those buildings considered, due to their high-elevation setting and reliance upon local wood, were built from temperature sensitive trees derived from stands close to the timberline. As most of the living trees span 400–500 years, assessment of the strength of this effect cannot be made with instrumental data, and must rely upon validation exercises. We note that in comparison to TRW, the climate response of MXD is more independent of site-ecology, elevation, and species (Frank and Esper, 2005; Büntgen et al., 2008a), and these potential problems would likely be greater when using TRW.

An important issue common to all extreme year analyses is the assessment of a reliable methodology, which is robust enough to account for artificial changes in inter-annual variance over time. Due to changes in sample replication and inter-series correlation, a higher number of extremes may for example be detected during the most recent centuries, during which samples originated from clearly defined forest stands. To reduce such problems related to changes in variance and homogeneity (see Frank et al., 2007a), extremes were herein detected in the individual measurement series where the variance was standardized, before being summed up to the chronology-level.

More cold summers were detected in comparison to warm ones (Fig. 2). More than a methodological issue, this is likely related to the nature of MXD and the association of wood anatomy and temperature. Tree growth at the upper treeline is mainly limited by temperature and growing season length (Tranquillini, 1979; Körner, 1998). Numerous studies have shown that radial growth and wood density of conifers varies under the influence of temperature (e.g., Fritts, 1976; Schweingruber et al., 1979). A cool and short growing season results in a narrow ring with low-density latewood (Hantemirov et al., 2004), whereas more favorable warmer conditions lead to wider rings with higher MXD (Frank and Esper, 2005). However, there is an upper range for MXD at ~1.3 g/cm^3 when the wood consists of no lumina but only cell walls (Kilpeläinen et al., 2003). If this upper threshold is approached, potential non-linear responses may be observed. Such anatomical properties of the wood structure could therefore explain why it is more difficult to record positive temperature extremes in latewood density, and require a more detailed understanding of intra-seasonal growth (Moser et al., 2010).

4.3. Instrumental uncertainty

Comparison with instrumental data showed that MXD-based extremes best capture an extended AMJJAS temperature signal. When seeking to verify the proxy characteristics for rare events, even exceptionally long instrumental records do not allow evaluation of proxy characteristics for more than a handful of positive and negative extremes. Over this recent time period we find good agreement between those events detected with different instrumental datasets. We observed "classical" extreme summers such as 1816 and 1912 that are likely related to summer cooling after volcanic eruptions (Briffa et al., 1998; D'Arrigo and Jacoby, 1999), or 2003 that is reported to be the warmest summer in Europe since 1500 (Luterbacher et al., 2004) or even since AD 755 (Büntgen et al., 2006a). However, some years, such as 1781, 1797, and 1799 are seen in the observations but not revealed in the MXD data. And similarly, 1774, 1921, and 1924 are MXD-based extremes not obvious from the instrumental readings. Potential reasons of such discrepancies have been broadly discussed and include: statistical uncertainty due to calibration methods applied (Cook and Kairiukstis, 1990), biological persistence in the tree-ring time series (Fritts, 1976; Frank et al., 2007b), non-linear growth–climate responses (Fritts, 1976), reduction of station measurements back in time (Auer et al., 2007), and their different homogenization adjustments (Frank et al., 2007b). While some of the discrepancies occur in the early-instrumental period, we do not believe that the long-term biases indicated for the Alps (Frank et al., 2007b) will play much of a role due to high-pass filtering of both the tree-ring and instrumental data. In contrast, increases in the intrinsic variance (Della-Marta et al., 2007) and the reduced number of stations reporting may yield a slightly less secure comparison with instrumental data back in time. Interestingly, an increase in intrinsic variability will cause preferential identification of extremes during the early period when using fixed threshold approaches. This will be problematic even for high-pass filtered data. Despite such uncertainties, a comparison between the MXD-based extremes and a JJA European temperature reconstruction (Luterbacher et al., 2004), however, confirmed similarities in the signal and also contributed towards understanding of the spatial characteristics of extremes.

4.4. Documentary uncertainty

In Europe, documentary data are relatively abundant between the mid 16th and the mid 18th centuries, and become less abundant not only further back in time, but also towards present when documentary data have been substituted with instrumental records (Brázdil et al., 2005; Jones et al., 2009). For this reason the analysis started from 1550. A primary uncertainty in documentary data is related to construction of temperature indices that depends on the quality and amount of available sources as well as their methodological interpretation (for more details see Brázdil et al., 2005).

The quality of documentary evidence may differ if evidence is based upon a climatic phenomenon that has physical meaning and constraints, such as lake freezing or summer snowfall, or if the reports are of a more anecdotal nature. Similarly, various observers are believed to be more or less reliable in their reporting. Unless documentary evidences were collected as part of a systematic set of observations, they tend to be focused on the occurrence of unusual or extreme events, with possible biases to events that have societal or economic consequences. Researching specific interpretation of various sources may lead to some uncertainties, but these may be small in comparison to the "Segment Length Curse" issues related to piecing numerous documentary sources together and focusing on extreme events (see Section 4.5). These latter two factors may limit the preservation of low-frequency signals, but if so this issue is not of central interest for the present study of extreme events.

As documentary data are often placed on an index scale (e.g., plus to minus three) there is some loss of information due to the more coarse precision. Calibration of documentary records is challenged by the ending of records towards present, in many, but not all cases, there may be too little or no overlap between documentary and instrumental data (Dobrovolný et al., 2010). Splicing of instrumental and documentary data is performed to develop a continuous timeseries towards present. This practice, however, may result in unwarrantedly high confidence in the quality of the documentary portion of the series, even if a certain amount of noise is added to the instrumental fraction of the series. With limited or no overlap between documentary and instrumental data, an estimation of the amount and character of noise to be added to the proxy is challenging. This may be critical to secondary users as the differing compositions in the documentary indices may not be clearly distinguished in subsequent publications. However, see Dobrovolný et al. (2010) for a noteworthy example where noise could be well assessed.

Some types of documentary evidence may also be subject to similar types of biological uncertainties as with the tree-ring data. For example, records of grape harvests, which usually correspond with warm season conditions, may be biased, for example, by particularly rainy Septembers, which foster diseases (Meier et al., 2007). Also, societal traditions and conditions such as warfare and activities based upon days of the week, and changes in practices or grape varieties may also lead to inaccuracies in documentary data (see Meier et al., 2007 and references therein). Some of these questions can be addressed as more proxy evidence is compiled and analyzed. The validation of documentary, tree-ring, and instrumental data as performed in this study, may be regarded as a step towards reducing uncertainties in our understanding of the noise in the various archives and the occurrence of extreme events over the past millennium.

4.5. Extremes in the context of low-frequency climate variation

We removed any lower frequency information from the MXD (and all other) data, assuming a flexible climatology, and thus assessing year-to-year variations that are not affected by the different problems related to the low-frequency tree-ring (Cook et al., 1995; Briffa et al., 1996; Esper et al., 2002; D'Arrigo et al., 2006) or documentary archives (Brazdil et al., 2005). This allows characteristic years to be placed in a context of surrounding decades and years, but ignores longer time-scale information such as the amplitude and transition from the Medieval Warm Period into the Little Ice Age and Modern Warmth (Frank et al., 2010).

The relative weighting of high- to low-frequency variance and the spectral properties of past climate variability are still under discussion. At one end of the spectrum, certain documentary evidences based upon personal accounts of weather extremes (Pfister et al., 2009) are constrained to a fraction of an individual's lifespan and appear to be limited when trying to reconstruct low-frequency information. The compilations of many short documentary series very likely have problems analogous to those described for tree-ring data as the "Segment Length Curse" (Cook et al., 1995). In tree-ring data these limitations may be overcome by techniques, such as Regional Curve Standardization (Esper et al., 2003) that can preserve low-frequency variance on time-scales longer than the individual segments (Esper et al., 2009). However, tree-ring chronologies where the autocorrelative structure has been removed (Cook, 1985), are most certainly biased towards the high-frequency domain. On the other hand, biological

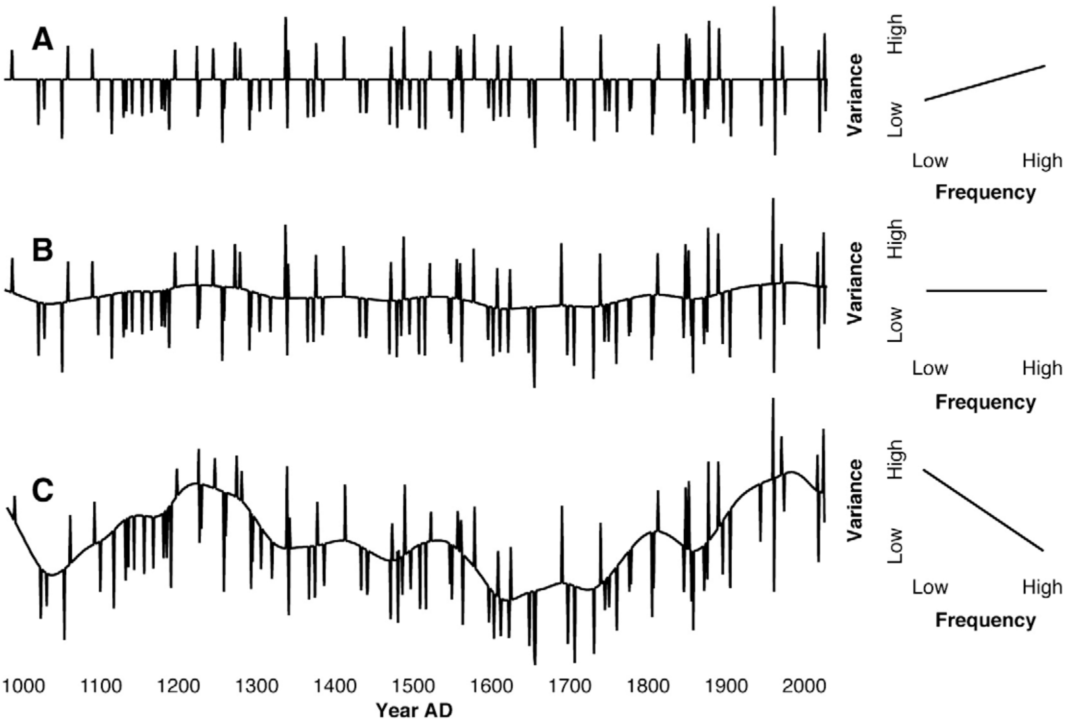

Fig. 6. Time series and schematic spectra for different weightings of high and low-frequency temperature of the combined MXD record (Fig. 2) and the low-pass filtered Büntgen et al. (2006a) summer temperature reconstruction. Spectral characteristics range from (A) blue noise, (B) white noise, to (C) and red noise.

autocorrelation often found in TRW data (Frank et al., 2007b) or reconstructions merging low- and high-resolution archives (Moberg et al., 2005) may contain too much long-term variability (Mann et al., 2005). Efforts to specifically calibrate the high- and low-frequency components separately (Osborn and Briffa, 2000) may be able to overcome some of these spectral characteristics, however, the reduced degrees of freedom in the low-frequency domain generally add uncertainty to such approaches.

To illustrate the challenges inherent in combining high- and low-frequency archives together, we provide three schematic approaches illustrating how extreme values derived herein can be combined with the low-frequency signal from the temperature reconstruction by Büntgen et al. (2006a), with the low-frequency climate reconstruction given different weights ranging from zero to approximately 50% of the variance of the merged series (Fig. 6). Spectral characteristics have been schematically illustrated and range from "blue" (more high- than low-frequency variance) to "white" (equal variance across all frequency domains), to "red" (more low-frequency variability). These schematic diagrams help indicate challenges in providing a comprehensive picture of low- to high-frequency climate variability over the past millennium. Although, our approach was successful in determining an appropriate classification scheme for extreme events and in developing a methodology able to identify and characterize the occurrence of extreme episodes back in time, further work is required to determine how properly weigh the high- and the low-frequency temperature components and how to better combine diverse proxy data. It should also be noted that the preservation and appropriate weighting of different frequency information applies to most if not to all existing studies. Although we do not solve this issue here, we (*i*) provide a simple illustration of the consequences of weighting uncertainties, and (*ii*) contribute to the on-going discussion and efforts to properly weight low to high-frequency variability (Osborn and Briffa, 2000; Osborn and Briffa, 2004; Mann et al., 2005; Moberg et al., 2005; Frank et al., 2007a; Moberg et al., 2008).

5. Conclusions

We developed a near millennium-long catalogue of temperature extremes for the Greater Alpine Region by merging three MXD-based timeseries. Challenges with the present approach included the classification of extreme events and development of a methodology to identify the frequency of extremes back in time. We notably detected a bias towards more faithfully reconstructed cold extremes in MXD data, and stressed the uncertain spectra of long-term temperature change. The comparison with long instrumental and documentary evidence suggests that the recorded extremes clearly coincide across archives. Based upon tree-ring and documentary evidence, we identified 44 extreme summers during the 1550–2003 period. Tree-ring data also provide indications for extreme cold and warm summers back until AD 1000. We suggest that this dataset will be useful towards a better understanding of the characteristics prior to the instrumental period, and allow links between the occurrence and frequency of extreme events over the Alps and large-scale climate variability and dynamics to be made. Specific characteristics of the tree-ring and documentary archives show both their limitations and strengths for multi-proxy climate reconstructions. This catalogue will allow assessment of the increasingly sparse and uncertain documentary evidence that are being made available for the first half of the past millennium. We note the importance of considering the seasonality of extreme events when comparing and combining various archives.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloplacha.2010.02.004.

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