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Original article

Testing the hypothesis of post-volcanic missing rings in temperature sensitive dendrochronological data

Jan Esper[a,*], Ulf Büntgen[b,e], Jürg Luterbacher[c], Paul J. Krusic[d]

[a] Department of Geography, Johannes Gutenberg University, 55099 Mainz, Germany
[b] Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland
[c] Department of Geography, Climatology, Climate Dynamics and Climate Change, Justus-Liebig University, 35390 Giessen, Germany
[d] Department of Physical Geography and Quaternary Geology, Stockholm University, 10691 Stockholm, Sweden
[e] Global Change Research Centre AS CR, v.v.i., Bělidla 986/4a, CZ-60300 Brno, Czech Republic

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ABSTRACT

The precise, annual dating control, inherent to dendrochronology, has recently been questioned through a combined analysis of tree-growth and coupled climate models (Mann et al. (2012; hereafter MAN12)) suggesting single tree-rings in temperature limited environments are missing following large volcanic events. We test this hypothesis of missing, post-volcanic rings by using a compilation of maximum latewood density (MXD) records that are typically used for reconstructing temperature and the detection of volcanic events, together with a unique set of long instrumental station data from Europe reaching back into the early 18th century. We investigate the temporal coherence between tree-ring MXD and observed summer temperatures before and after the most significant, precisely dated, volcanic event of the past 1000 years, the 1815 Tambora eruption widely known as the cause for the 1816 “year without a summer”. Comparison of existing and newly developed MXD chronologies from cold environments in Northern Scandinavia ($\bar{r}_{\text{North}} = 0.70$, $N = 3$) and the European Alps, including the Pyrenees, ($\bar{r}_{\text{Central}} = 0.46$, $N = 4$) reveals significant interseries correlations over the 1722–1976 common period, suggesting coherence among these independently developed timeseries. Comparisons of these data with observed JJA temperatures – from 1722 to 1976, a 94-year pre-Tambora (1722–1815), and a 94-year post-Tambora (1817–1910) period – reveals significant and temporally stable correlations ranging from 0.32 to 0.68. However, if we assume the 1816 ring is missing in the MXD chronologies (i.e., shift the pre-Tambora data by one year), all proxy/instrumental correlations fall apart approaching zero. Results from an additional experiment, where the long instrumental record is replaced by an annually resolved, 500-year, summer temperature reconstruction derived from documentary evidence, corroborates the findings from the first experiment: significant positive correlations with the unmolested chronologies and zero correlation with the perturbed chronologies back to 1500 AD. These elementary analyses indicate that either the tree-ring chronologies are correctly dated, i.e., no is ring missing in the year without a summer, or that both the long instrumental and documentary records contain dating uncertainties. As the latter is unlikely, we conclude the MAN12 hypothesis on post-volcanic missing rings can be rejected based on simple comparisons of tree-ring, instrumental and documentary data over the past 300–500 years from Central and Northern Europe.

Introduction

A recent study (MAN12) comparing pseudoproxies created by a linked climate and tree growth model with a hemispheric scale network of temperature sensitive tree sites (D’Arrigo et al., 2006), concluded that tree-rings in years following very large volcanic eruptions, such as the 1815 Tambora, the 1452/53 Kuwae and the 1258/59 unknown events, are missing. Stem cambial activity in these post-volcano years is presumed to shut down entirely, as summer temperatures fall below a parameterized threshold. These effects are supposed to be of large-scale nature, i.e., the rings are missing in all trees in a number of thermally limited environments so that crossdating techniques (Holmes, 1983) would fail to detect these errors within and between sampling sites. They are expected to have occurred repeatedly throughout the past millennium permitting chronological dating errors to accumulate back in

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* Corresponding author. Tel.: +49 6131 3922296; fax: +49 6131 3924735.
E-mail address: esper@uni-mainz.de (J. Esper).

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time. This "age-model error" (hereafter AME) is supposed to affect all regional temperature reconstructions derived from tree-rings (e.g., Esper et al., 2002b, 2003, 2010; Cook et al., 2004; Luterbacher et al., 2004; Büntgen et al., 2005, 2011; Treydte et al., 2006; Kress et al., 2010), such that annually resolved, large-scale reconstructions of the past millennium, relying on dendrochronological data (e.g., Crowley and Lowery, 2000; Esper et al., 2002a; Juckes et al., 2007; Mann et al., 2008; Frank et al., 2010; Ljungqvist et al., 2012), and used in detection (e.g., Briffa et al., 1998; Esper et al., 2007a; Salzer and Hughes, 2007; Breitenmoser et al., 2012) and attribution (e.g., Hegerl et al., 2006, 2011) studies, contain dating uncertainties of at least 3 years.

The MAN12 model suggests much cooler summer temperatures in post-volcano years than revealed in real world tree-ring data (D'Arrigo et al., 2006). The growth model utilized in MAN12 is a simplified variant of the Vaganov–Shashkin model (Vaganov et al., 2006), which requires a number of empirically derived parameters, including a minimum temperature threshold for cambial activity that was erroneously defined as 10 °C (Körner, 2012). According to MAN12, the observed discrepancy between their modelled climate and growth responses versus real-world tree-ring data supports the occurrence of missing rings in thermally limited environments. No attempt has been made to assess the crossdating technique (Holmes, 1983) that is typically used to identify missing rings within and among tree-ring sites, however.

The AME hypothesis has far-reaching consequences for the field of Dendrochronology and related sciences relying on the precise, annual, dating of tree-ring chronologies and therefore requires testing before being considered. We report on such a test using MXD data from trees growing in marginally favourable, thermal environments in Northern and Central Europe, with particular attention to the pre- and post-Tambora (1815) periods, to assess the chronologies' common variance and the crossdating integrity within these regions. The MXD chronologies utilized here have been developed over many years by multiple laboratories and researchers and combine multiple lines of evidence from various high altitude and high latitude sites in Europe. The Tambora event represents an extreme case for the assessment of the AME hypothesis as it represents the largest annually dated volcanic eruption (Siebert et al., 2010) for which severe cold has been reported in Central Europe (Stothers, 1984).

Tree-ring chronologies are compared with instrumental station data reaching back into the early 18th century and an independently developed, annually resolved, summer temperature reconstruction based on documentary evidence back to 1500 (Dobrovolný et al., 2010). These basic assessments rely on the assumptions that (i) no dating error is inherent to the observational and documentary data, and that (ii) the tree-ring/instrumental and tree-ring/documentary associations remain stable through time and do not change significantly between the pre- and post-Tambora periods.

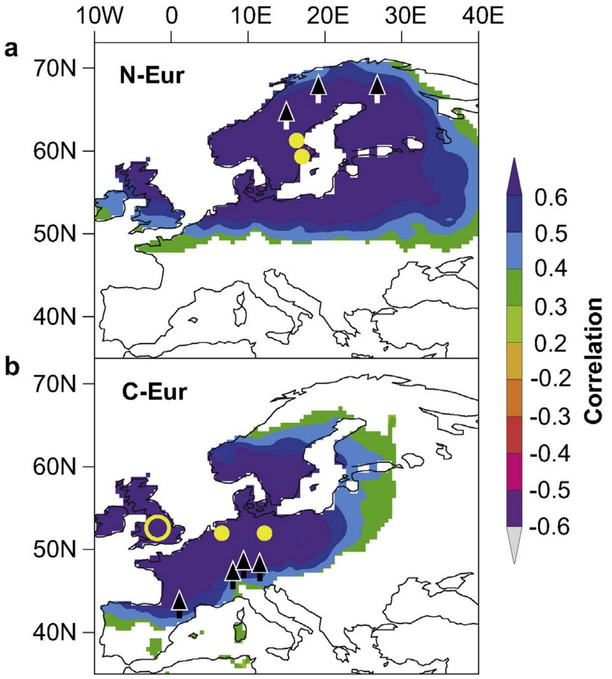

Fig. 1. Location of long-term instrumental station and tree-ring MXD records in Europe. (a) Jae, Tor, and Nsc MXD records (black triangles from west to east) and Uppsala and Stockholm stations (yellow circles, north to south) in Northern Europe. (b), Pyr, Loe, Lau, and Tir MXD records (black triangles, west to east) and Central England, De Bilt, and Berlin stations (yellow circles, west to east) in Central Europe. Central England is a composite of several observing sites. Contours indicate correlation patterns of mean JJA temperatures of the (a) Northern and (b) Central European station records against CRU TS 3.1 summer temperatures over the common 1901–1976 period ($p < 0.01$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Materials and methods

Seven multi-century MXD chronologies spanning the past 500+ years have been developed over the past three decades in Northern and Central Europe (Fig. 1). Three of these records, Jae (Gunnarson et al., 2010), Tor (Briffa et al., 1992), and Nsc (Esper et al., 2012), are derived from Scots pine (*Pinus sylvestris*) trees in Northern Fennoscandia, close to the latitudinal (Tor and Nsc) and elevational (Jae) distribution limits (Table 1). These records have been reported to contain medium (Jae) to high (Tor and Nsc) summer temperature signals. Tree-ring width measurements from these compilations – that are derived from the same dated rings as MXD – have been used in a number of large-scale climate reconstructions (Büntgen et al., 2012). The Nsc record has only recently been developed and integrates a substantially larger number of density measurement series than the other MXD records (see Esper et al., 2012 for details).

Table 1
MXD site chronologies and long-term instrumental station records from Northern and Central Europe. The Lau chronology ends in 1976. Last column refers to periods common to all tree-ring and the shorter (Sto, Ber) and longer (Upp, Cet, Dbi) station records.

Chronology	Country	Species	Source	Station	Country	Period
N-Eur						
Jaemtland (Jae)	Sweden	Pine	Gunnarson et al. (2010)	Uppsala (Upp)	Sweden	1722–1976
Tornetraesk (Tor)	Sweden	Pine	Briffa et al. (1992)	Stockholm (Sto)	Sweden	1756–1976
N-Scan (Nsc)	Finland	Pine	Esper et al. (2012)			
C-Eur						
Pyrenees (Pyr)	Spain	Pine	Büntgen et al. (2008)	Centr. England (Cet)	England	1722–1976
Lauenen (Lau)	Switzerland	Spruce	Schweingruber et al. (1988)	De Bilt (Dbi)	Netherlands	1722–1976
Lötschental (Loe)	Switzerland	Larch	Büntgen et al. (2006)	Berlin (Ber)	Germany	1756–1976
Tirol (Tir)	Austria	Spruce	Esper et al. (2007a,b,c)			

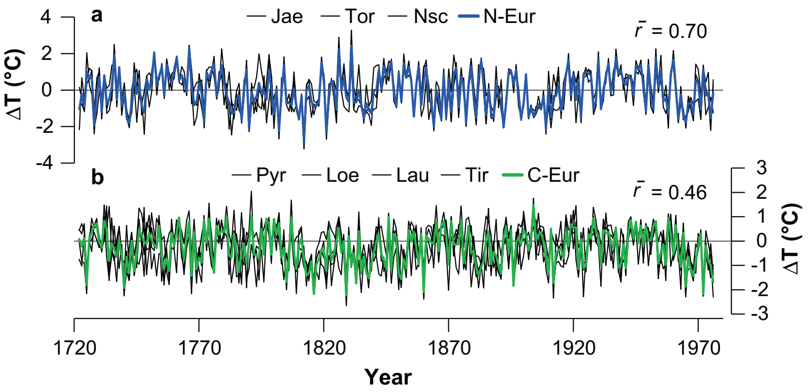

Fig. 2. Northern and Central European tree-ring MXD records shown over their common 1722–1976 period. (a) Jae, Tor, and Nsc site chronologies and their arithmetic mean (N-Eur). (b) Pyr, Loe, Lau, and Tir site chronologies and arithmetic mean (C-Eur). All MXD data were detrended using negative exponential growth functions, and the mean timeseries for each site scaled to JJA temperatures of the closest grid point derived from CRUTEM4 (departures from 1961 to 1990 mean; Jones et al., 2012). N-Eur and C-Eur derived from averaging the three northern and four central site chronologies, and scaling to the mean JJA timeseries of two northern and three central grid points. $\bar{r}$ values refer to interseries correlations among MXD site chronologies in Northern and Central Europe over the 1722–1976 common period.

The four Central European MXD sites are spread over a larger area (in comparison to the northern sites), including records from the Pyrenees (Pyr; Büntgen et al., 2008), Switzerland (Lau and Loe; Schweingruber et al., 1988; Büntgen et al., 2006) and Austria (Tir; Esper et al., 2007b). The oldest of these records (Lau) was developed in the 1980s thus constraining the common period end date for all subsequent analysis to 1976. The Central European compilation contains chronologies derived from spruce (*Picea abies*), larch (*Larix decidua*), and pine (*P. sylvestris* and *Pinus uncinata*) trees, and their summer temperature signals are lower in comparison to the Northern Europe MXD data (the weakest being Pyr and Lau; see Büntgen et al., 2010 for details on their spatial significance).

Different research teams, involving generations of experienced technicians over the past 30+ years, worked on the development of the MXD data used in this study. Measurements were obtained from a Walesch X-ray densitometer (Schweingruber et al., 1978), crossdated using light tables and verified using the program Cofecha (Holmes, 1983). All MXD data were detrended by calculating ratios from negative exponential and straight line functions (no positive slope; Fritts, 1976). Site chronologies were developed using the bi-weight robust mean and variance stabilized to account for changes in sample replication and coherence throughout time (Frank et al., 2007b). Coherence among the MXD chronologies is assessed by calculating their interseries correlation ($\bar{r}$; Cook and Kairiukstis, 1990) over the 1722–1976 period, the time span common to all tree-ring and instrumental climate data. Site chronologies are transferred into mean JJA temperature estimates, expressed as departures from a 1961 to 1990 mean, by scaling the records to the mean and variance of the closest CRUTEM4 grid point (Jones et al., 2012) over the 1901–1976 period (Fig. 2; for detailed calibration results see the original papers listed in Table 1).

The MXD-based temperature estimates are compared with long-term instrumental station records from Uppsala (Ups; Moberg and Bergström, 1997) and Stockholm (Sto; Moberg and Bergström, 1997; Moberg et al., 2002, 2003) in Northern Europe, and Central England (Cet; Manley, 1974), De Bilt (Dbi; van den Dool et al., 1978; van Engelen et al., 2001), and Berlin (Ber; Vose et al., 1992) in Central Europe (Table 1). These stations (with the exception of Sto) were displayed in the 2007 IPCC report (Solomon et al., 2007, p. 467) representing some of the longest instrumental records worldwide and are deemed reliable estimates of past climate variability. The period from 1722 to 1976, considered here for cross-validation, is continuously covered by three of the aforementioned stations, and the shorter 1756–1976 period by all five stations. JJA temperatures from each station, as well as regional means of the two northern (Upp, Sto) and three central (Cet, Dbi, Ber) stations – representing summer temperature patterns in Northern and much of Central Europe (see colour code in Fig. 1) – are used for assessing the integrity of tree-ring MXD data. Whereas the northern tree sites (Jae, Tor, and Nsc) are located close to the area represented by the UppSto station mean, the central tree sites (Pyr, Lau, Loe, and Tir) are located significantly south and east of the area covered by the CetDbiBer mean. Consequently, somewhat lower proxy/instrumental coherence is to be expected for these latter MXD sites. It should also be noted that JJA is not necessarily the optimum season of maximum temperature response for all of the MXD sites (see the original papers listed in Table 1 for details; for Lau, Loe, and Tir see also Battipaglia et al., 2010).

The tree-ring MXD records are also compared with an annually resolved, 500-year, summer temperature reconstruction derived from documentary evidence (Dobrovolný et al., 2010). This reconstruction combines a documentary-based index series from Germany, Switzerland and the Czech Republic, from 1500 to 1854, with instrumental data from eleven regional stations. The original scale of the documentary index series (ranging from −3 to +3) was transferred into JJA temperatures through calibration against homogenized instrumental data from 1771 to 1854 ($r = 0.77$, see Dobrovolný et al., 2010 for details). The instrumental data were corrected for insufficient radiation protection of early thermometers and urban heat island effects (Böhm et al., 2010).

As with the long station records, we assessed the tree-ring/documentary coherence through time using 30-year running correlations. To evaluate the impact of potentially missing, post-volcanic rings, the pre-Tambora MXD series were shifted by one year into the past (assuming that the 1816 ring is missing in the tree-ring datasets) and running correlations re-calculated using these shifted data. For the tree-ring/instrumental data comparison we additionally considered two distinct 94-year periods (1722–1815 and 1817–1910) pre- and post-the "year without a summer" using both the original and shifted MXD data to assess the influence of a potentially missing ring in 1816.

Results

The Northern and Central European MXD site chronologies share a high degree of common variance suggesting these, independently developed and crossdated, chronologies are either correctly dated or all contain exactly the same AME (Table 2). Interseries

Table 2
Coherence of tree-ring and instrumental station timeseries. Pairwise correlations for (a) MXD site chronologies, and (b) long-term JJA temperature records, over the 1722–1976 (top right) and 1756–1976 (bottom left) periods. Sto and Ber stations extend back to only 1756. Colours (from light to dark) indicate coefficients 0.2–0.4, 0.4–0.6, 0.6–0.8, >0.8.

a

1722-1976

1756-1976

	Nsc	Tor	Jae	Loe	Lau	Tir	Pyr
Nsc		0.79	0.67	0.06	0.06	0.04	-0.09
Tor	0.81		0.65	0.01	0.05	0.11	-0.15
Jae	0.67	0.67		0.04	0.07	0.07	-0.08
Loe	0.06	0.02	0.02		0.64	0.54	0.42
Lau	0.06	0.03	0.04	0.69		0.61	0.36
Tir	0.06	0.11	0.07	0.56	0.63		0.20
Pyr	-0.06	-0.11	-0.08	0.45	0.40	0.23	

b

1722-1976

1756-1976

	Upp	Sto	Cet	Dbi	Ber
Upp			0.41	0.54	
Sto	0.93				
Cet	0.45	0.48		0.78	
Dbi	0.57	0.63	0.79		
Ber	0.66	0.66	0.53	0.75	

correlations, calculated over the 1722–1976 period, are 0.70 among the northern sites, and 0.46 among the central sites, justifying the calculation of two regional mean curves, N-Eur and C-Eur, respectively. The lower $\bar{r}$ value among the Central European timeseries is in part due to the greater distance between the Spanish Pyrenees site (Pyr) and the Swiss and Austrian sites Lau, Loe, and Tir. The Lau dataset is also from a lower elevation, about 600 m below treeline (2.200 m.a.s.l.), but still correlates >0.6 with Loe and Tir over the 1756–1976 and 1722–1976 periods.

As with the tree-ring data, the nearby instrumental station records in the north correlate better ($r_{1756–1976} = 0.93$) compared to the central stations ($\bar{r}_{1756–1976} = 0.69$). The lowest correlation within these regions is obtained between the distant Cet and Ber records ($r_{1756–1976} = 0.53$). Significant correlations are also obtained between the northern and central stations, a feature that is unapparent between the more remote northern and central MXD chronologies (Table 2).

When compared with the long-term instrumental data, the MXD chronologies reveal significant correlations ranging from 0.40 to 0.68 in Northern and 0.16–0.44 in Central Europe over the common 1722–1976, early 1722–1815, and late 1817–1910 periods (Fig. 3). The substantially lower results in Central Europe are likely related to (i) the larger distance between tree-ring and instrumental sites, (ii) the lower coherence among the tree-ring and among the station records, and (iii) the overall weaker climate signal of the alpine in comparison to the latitudinal treeline sites (Tor and Nsc in Northern Fennoscandia, see original papers listed in Table 1). Interestingly, Jae showed the highest correlation of the northern tree sites, likely due to this site's proximity to the Upp and Sto stations. In the central region, Loe correlates best with the CetDbiBer station mean.

These tree-ring/climate associations all fall apart if we assume the post-Tambora 1816 ring to be missing (orange bars in Fig. 3). Shifting the pre-Tambora tree-ring data by one year reduces the early 1722–1815 correlations of the N-Eur and C-Eur series from 0.53 and 0.41–0.02 and 0.03, respectively (Fig. 4). Application of the AME hypothesis also misaligns the conspicuous low- and high-density layers (the grey bars in Fig. 4) that are vital for crossdating tree-ring data.

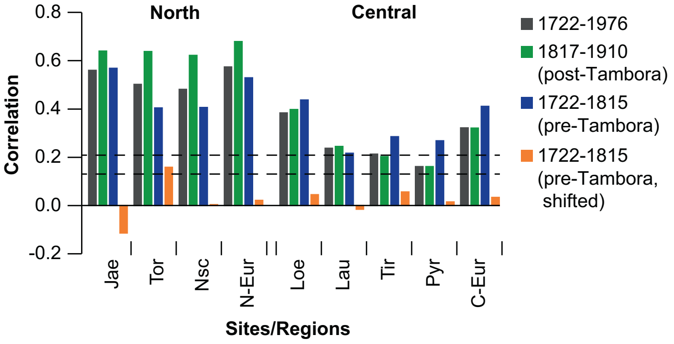

Fig. 3. Tree-ring correlation patterns against long-term temperature data. Spearman coefficients derived from correlating the northern Jae, Tor, and Nsc MXD site chronologies and their mean (N-Eur) with UppSto JJA mean temperatures, and the central Loe, Lau, Tir, and Pyr site chronologies and their mean (C-Eur) with CetDbiBer JJA mean temperatures, over the full period of overlap (1722–1976, grey), 94 post-Tambora years (1817–1910, green), and 94 pre-Tambora years (1722-1815, blue). Orange bars show results for the pre-Tambora period, after shifting the tree-ring timeseries by one year into the past (i.e., assuming that the 1816 ring is missing in all MXD data). Significance thresholds ($p < 0.05$) indicated by dashed lines for the 94 year and 255 year periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

The obvious misfit, when assuming a missing tree-ring in the year without a summer, is further emphasized by 30-year running correlations calculated against the long instrumental and documentary data back to 1722 and 1500, respectively (Fig. 5). The moving window approach accentuates the temporally changing signal strength typical of proxy data containing large noise fractions and helps identify those weakly associated timeseries (e.g., site Pyr in Fig. 5a; though note the large distance to the instrumental data and the influence of a Mediterranean climate regime on this site). Shifting the pre-Tambora MXD series also results in a noticeable decline in correlation that is most striking in the northern tree sites, those with otherwise the strongest temperature signal. Correlations of the shifted data fluctuate around zero, a finding that is supported in both the Northern and Central European examples back to 1722 based on instrumental data, and in Central Europe back to 1500 based on documentary data. When applying the MAN12 AME hypothesis, the tree-ring/documentary correlations drop from 0.63 to 0.05 over the 16th century (Fig. 5c).

Discussion and conclusion

Simple correlation analysis among European MXD chronologies as well as between the MXD chronologies and instrumental or documentary data show the proxy archives and observations are in agreement prior to the most severe, precisely dated, volcanic event of the past 1000 years, the 1815 Tambora eruption. Considering some of the correlations between MXD and instrumental and documentary data reported here are quite high (mostly $p < 0.001$), and the subsequent drop in correlation after shifting the chronologies is substantially low (mostly $r \approx 0$), it appears very unlikely that the AME hypothesis is correct. Alternatively, there could be synchronous dating errors in the instrumental and documentary data that, theoretically, would corroborate the AME hypothesis. However, this appears equally unlikely.

Other approaches that could help test the AME hypothesis include assessments of (i) tree-ring data along elevational (e.g., Esper et al., 2007c; Moser et al., 2010) and latitudinal (e.g., Schmitt et al., 2004) transects, and of (ii) growth responses following earlier volcanic events, such as the 1258/59 unknown and 1452/53 Kuwae eruptions mentioned in MAN12. Studying the coherence of tree-ring data from treeline and non-treeline sites during pre- and

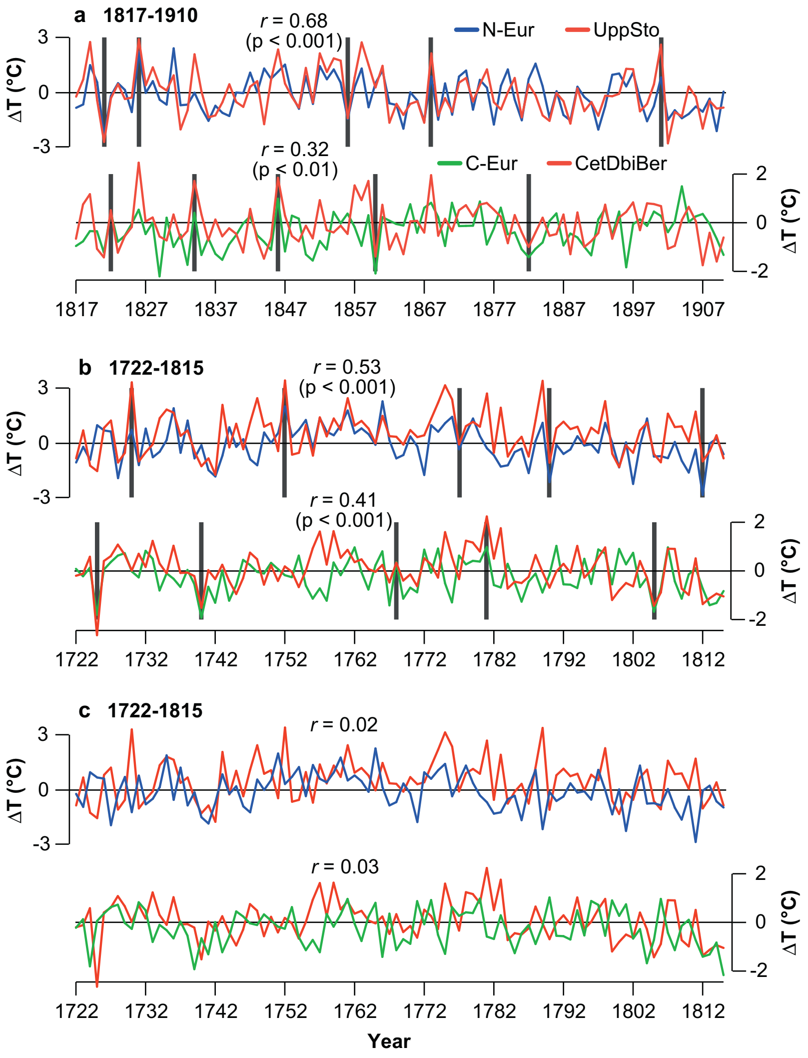

Fig. 4. Coherence between regional tree-ring and instrumental temperature timeseries. N-Eur (blue) and C-Eur (green) MXD records shown together with JJA mean temperatures of UppSto and CetDbiBer (red) over 94 years after ((a) 1817–1910) and before ((b) 1722–1815) the 1816 post-Tambora year. (c) Same as in (b), but assuming that the 1816 tree-ring is missing in all datasets, i.e., MXD timeseries shifted by one year into the past. Grey bars indicate years of common growth and temperature variations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

post-volcanic periods could be useful as MAN12 suggest AME to be restricted to thermally limited environments. This premise is, however, conflicting with long-standing dendroarchaeological dating and provenancing experiences in Northern Europe, the Baltics, and the Greater Alpine Region, for example (e.g., Behre, 1969; Bonde et al., 1997; Haneca et al., 2005). Analyses of earlier volcanic eruptions, on the other hand, would likely suffer from circular reasoning as the, still insecure, dating of these events has been settled by tree-ring evidence in the first place (e.g., Briffa et al., 1998; Salzer and Hughes, 2007; but see also Plummer et al., 2012).

Reasons for the failure of the AME hypothesis, when applied to real-world tree-ring data, are most likely related to the uncertainties and implementation of the climate and tree growth models utilized in MAN12. The theory of missing rings in treeline environments is driven by the unlikely, modelled, post-volcanic cooling rates of about 2 °C and the surprisingly milder temperature response found in a hemispheric tree-ring network (D'Arrigo et al., 2006). This discrepancy rather reinforces the uncertainties of climate-model simulations, as AME does not apply to real-world tree-ring data from Europe, i.e., does not "bolster the case for a significant influence of explosive volcanism on climate in past centuries" (MAN12). Other assumptions considered in the MAN12 tree growth model, such as the 10 °C minimum threshold for cambial inactivity, are also unrealistic (see Anchukaitis et al., 2012 for details), and attempts to test the effects of removing tree-rings from dendrochronological datasets have not been made. Removing only a fraction of tree-rings in particular post-volcanic years (e.g., 50%), which MAN12 hypothesized could dampen the cooling signature in climate reconstructions, is conflicting with the cross-dating technique applied within and among tree-ring sites (Fritts, 1976; Holmes, 1983; Cook and Kairiukstis, 1990).

The elementary empirical test carried out here, demonstrating that no post-volcanic ring is missing in European MXD data, suggests that other temperature sensitive tree-ring timeseries, including the D'Arrigo et al. (2006) network, which includes some of the same sites considered here, are free of AME. Finally, the D'Arrigo et al. (2006) network is based only on ring width data. Measurements of tree-ring widths are, admittedly, not well-suited for the analysis of post-volcanic effects as the tree's biological memory, inherent to this parameter (Frank et al., 2007a), conceals the impact of extreme climatic events which are otherwise more distinct in MXD data (e.g., Briffa et al., 1998). Nevertheless, as MXD and

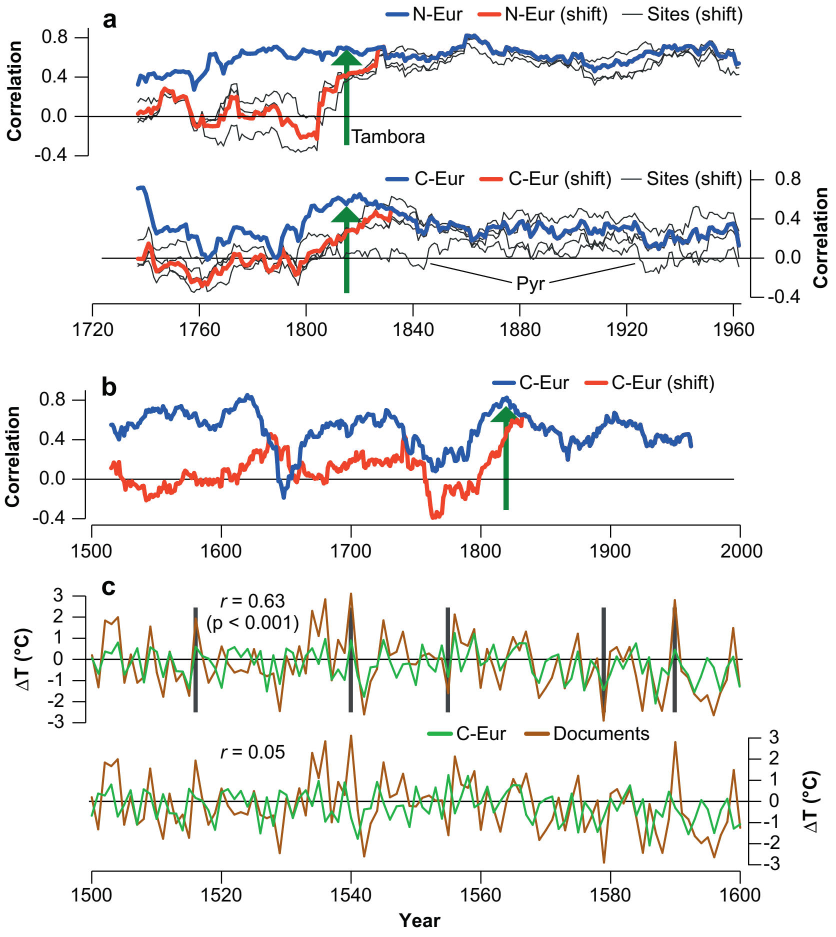

Fig. 5. Tree-ring coherence with long-term station and documentary records. (a) Centred 30-year running correlations between northern MXD records (Jae, Tor, Nsc, and N-Eur) and UppSto JJA mean temperatures, and central MXD records (Pyr, Lau, Loe, Tir, and C-Eur) and CetDbiBer JJA mean temperatures. Red curves show correlations after shifting the tree-ring records by one year, assuming a missing ring in 1816. (b) Centred running correlations between the mean MXD C-Eur record and regional JJA temperatures derived from documentary evidence back to AD 1500 (Dobrovolný et al., 2010). Red curve as in (a). Significance ($p < 0.05$) is reached at $r \approx 0.35$ in (a) and (b). (c) Coherence between the Central European tree-ring and documentary records throughout the 16th century. Lower panel shows the match after shifting the tree-ring record by one year, assuming a missing ring in 1816. Grey bars indicate years of common tree-ring and documentary variations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

ring width measurements are derived from the same tree-rings, the conclusion of an “increased temporal smearing back in time”, as proposed by MAN12, can be rejected for both parameters.

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