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Testing long-term summer temperature reconstruction based on maximum density chronologies obtained by reanalysis of tree-ring datasets from northernmost Sweden and Finland

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Abstract

Here we analysed the maximum latewood density (MXD) chronologies of two published tree-ring datasets: from Torneträsk region in northernmost Sweden (TORN, Melvin et al., 2013) and from northern Fennoscandia (FENN, Esper et al., 2012). We paid particular attention to the MXD low-frequency variations to reconstruct long-term summer (June–August, JJA) temperature history. We used published methods of tree-ring standardization: regional curve (RC) standardization, combined with signal-free (SF) implementation. Comparisons with a single-RC (RC1) and multiple-RC (RC2) were also carried out. We develop a novel method of standardization, the correction (C) implementation to SF (hence, RC1SFC or RC2SFC), tailored for detection of pure low-frequency signal in tree-ring chronologies. In this method, the error in RC1SF (or RC2SF) chronology, is analytically assessed and extracted to produce a RC1SFC or RC2SFC chronology. In TORN, the RC1SF chronology shows higher correlation with summer temperature (JJA) than RC1SFC, whereas in FENN the temperature signals of RC1SF chronology is improved by correction implementation (RC1SFC). The highest correlation between differently standardized chronologies for two datasets is obtained using FENN-RC2SFC and TORN-RC1 chronologies. Focusing on lowest frequencies, the importance of correction becomes obvious as the chronologies become progressively more correlative with RC1SFC and RC2SFC implementations. Subsampling the FENN data (which presents a higher number of samples than TORN dataset) to the chronology sample size of TORN data shows that the chronologies consistently bifurcate during the 7th, 9th, 17th and 20th centuries. We used the two MXD datasets to reconstruct summer temperature variations over the period −48–2010 calendar years. Our new reconstruction shows multi-decadal to multi-centennial variability with changes in the amplitude of the summer temperature of 2.6 °C in average during the Common Era.

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1 Introduction

Dendrochronology is one of the most common methods for obtaining the late Holocene reconstructions of past climate variability because tree-ring chronologies are high-resolution indicators of exactly dated paleoclimate information (Fritts, 1976). Moreover, tree-ring chronologies around the extra-tropical Northern Hemisphere contain clear climatic signals of summer temperatures (Briffa et al., 2002). This dendroclimatic association is notably high for different tree species growing near their polar and alpine range of distribution. Yet, the strength of this dendroclimatic response depends on the measured tree-ring parameter. While the use of tree-ring width chronologies as indicators of past climate variability has a long tradition in dendroclimatology, the development of X-ray based estimates of wood density fluctuations (Schweingruber et al., 1978) have increased the value of dendrochronology as an integral part of paleoclimatology. Several studies have shown that the measurements of maximum latewood densities (MXD) yield chronologies with improved climatic signal (Briffa et al., 2002). Consequently, the MXD chronologies from several regions around Eurasia and North America have been used for summer temperature reconstructions (Hughes et al., 1984; Davi et al., 2003; Luckman and Wilson, 2005; Büntgen et al., 2008).

Similar studies have been conducted in northern Fennoscandia where a few reconstructions of summer temperatures (JJA) over the Common Era have been based on MXD records of living and subfossil pines (Briffa et al., 1988, 1990, 1992, 1996; Briffa and Schweingruber, 1992; Büntgen et al., 2011; Esper et al., 2012). While the early studies concentrated on materials from northernmost Sweden, particularly the Torneträsk region (Schweingruber et al., 1988; Briffa et al., 1990, 1992, 1996; Grudd, 2008), the MXD tree-ring materials from northern Finland (Eronen et al., 2002) have recently been exploited. These materials have notably increased the available MXD sample size and temporally extended chronology for the region till BC 138 (Büntgen et al., 2011; Esper et al., 2012). In the most recent dendroclimatic analysis Melvin et

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al. (2013) used the subfossil (Schweingruber et al., 1988) and updated (Grudd, 2008) MXD data from Torneträsk.

A brief literature review exemplifies several inconsistencies in the published palaeoclimate indications. While all the published papers do emphasize the superior quality of MXD for their summer temperature reconstructions, there are troubling inconsistencies with temperature amplitudes and timing of events. While the first of these reconstructions (Briffa et al., 1992) strove to define the degree of the twentieth century warmth in the context of the last 500 yr, the subsequent study (Grudd, 2008) demonstrated a positive temperature anomaly of about 0.7–1.5 °C (30 yr mean) for the Medieval Warm Period (MWP) relative to the twentieth century conditions (1951–1970 mean). It also showed a cooling phase (up to 1.1 °C negative anomaly for 30 yr mean) for the Little Ice Age (LIA). However, Büntgen et al. (2011) did not find evidence for a cool period during the LIA interval. Esper et al. (2012) stated that the previously estimated warmth of the MWP may be notably *under*estimated. This study also revealed a previously undiscovered millennial scale cooling trend spanning the period between 138 BC and AD 2006 (Esper et al., 2012). Another detailed dendroclimatic analysis (Melvin et al., 2013) presented MWP temperatures at the level similar to the modern ones in the region suggesting an *over*estimation of the Medieval warmth published by Grudd (2008). Clearly, the details of the MXD based long-term temperature variability in northern Fennoscandia remains unclear. This situation is even more unsatisfactory, if not worrisome, considering the important role of the particular MXD data (Briffa et al., 1992, 1996) in several hemispheric and frequently cited paleoclimate reconstructions of the Common Era (e.g. Jones et al., 1998; Esper et al., 2002; Osborn and Briffa, 2006; Mann et al., 2009; Ljungqvist et al., 2012).

We assume that the climate variability within the region is likely too uniform to have caused the reported deviations in the published temperature reconstructions from adjacent regions of northernmost Sweden (Torneträsk) and Finland. Instead, the reasons for these deviations may more realistically stem from the microdensitometric and tree-ring standardization methods, as well as non-climatic noise inherent to the sample size variations. Indeed, the flip side of this dendroclimatic improvement from the tradition to simply register the widths of the rings to the more sophisticated MXD is the complexity of methods required to produce the high-resolution wood density profiles. As a pitfall, even marginal changes in the microdensitometry methods may produce significantly altered MXD data (Helama et al., 2010c, 2012). Tree-ring standardization, on the other hand, is an unavoidable process where the initial measurement series are transformed into dimensionless indices to remove the biological (i.e., non-climatic) growth variations prior to dendroclimatic interpretations (Fritts, 1976). Different standardization methods produce chronologies with deviating characteristics, and particularly the long-term (i.e., low-frequency) estimation of dendroclimatic signals is sensitive to the applied method (Briffa et al., 1992; Esper et al., 2002; Helama et al., 2004). Indeed, the recent reanalysis of the Torneträsk MXD data detailed a set of estimation biases originating either from changes in the microdensitometry practices and tree-ring standardization (Melvin et al., 2013). Yet, these biases do not fully explain the obtained differences between the Torneträsk (Melvin et al., 2013) and larger Fennoscandian MXD data (Esper et al., 2012). Moreover, all the discussed studies used the same type of standardization method, the regional curve standardization (RCS; Briffa et al., 1992), to produce the MXD chronologies as proxy for temperature reconstructions. While this particular method is capable of producing chronologies with preserved low-frequency variations (Briffa et al., 1992; Esper et al., 2002; Helama et al., 2004), it is also more sensitive to data heterogeneity and therefore requires higher sample replication than other commonly applied standardization methods (Briffa and Melvin, 2011). Moreover, recent years have seen a diversification of the original RCS method, with development of its signal-free implementation (Melvin and Briffa, 2008) and its subsequent correction (Matskovsky, 2011), as well as multiple RCS approaches (Helama et al., 2005; Nicault et al., 2010; Melvin et al., 2013). The recent versions of the Torneträsk and Fennoscandian chronologies have used the RCS along with its variations (Esper et al., 2012; Melvin et al., 2013) but so far no systematic study exists to present the construction of the resulting MXD chronologies using consistent tree-ring standardization.

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Here we reanalyze the two MXD datasets from Torneträsk (Melvin et al., 2013) and more largely from Fennoscandia (Esper et al., 2012) using identical standardization. MXD variations in the data were identified in detail and the same types of RCS method were applied to both datasets, dealing with the potential effects from microdensitometry and standardization methods. We calibrate standardized MXD data to instrumental JJA temperatures of the Tornedalen climate record located in northern Sweden covering the last 200 yr (Klingbjer and Moberg, 2003). Then we extrapolate our observation to reconstruct regional summer temperature over the Common Era.

2 Materials and methods

2.1 Geographical setting

This study is based on X-ray based microdensitometic data of modern and subfossil Scots pine (*Pinus sylvestris* L.) tree-rings. We use published and online archived MXD data from northernmost Sweden (i.e., Torneträsk region) and northern Fennoscandia. These datasets are referred to as TORN (Schweingruber et al., 1988; Grudd, 2008; Melvin et al., 2013) and FENN (Esper et al., 2012).

Originally, the collection of the TORN material was carried out in five individual sites around the Lake Tornesträsk (68°10′–68°20′ N to 19°45′–20°45′ E; 400–470 m above sea level, Fig. 1). Three of these localities provided subfossil tree-rings for extending the chronology back in time till AD 436 (Bartholin and Karlén, 1983; Bartholin, 1987). The MXD chronology for TORN was produced by Schweingruber et al. (1988) and updated with more recent material of living trees by Grudd (2008) and Melvin et al. (2013). The TORN data now covers the period AD 441–2010 and can be downloaded via http://www.cru.uea.ac.uk/cru/papers/melvin2012holocene/.

The subfossil FENN material of Eronen et al. (2002) originates from the region of northern Finland. A portion of this material, covering roughly the past two millennia (since 138 BC) was later used to build a new MXD chronology for the region (between 66.80° and 69.50° N; 23° and 29° E; 190 and 340 m above sea level, Fig. 1). The subfossil material was updated with living tree material from North-West Finnish Lapland and northernmost Sweden (Esper et al., 2012). Actually, one of the living tree sites included in the FENN dataset is from the Torneträsk region. As a result, the modern part of the FENN dataset is weighted towards the west, while the eastern half of region is represented only by subfossil sites. Moreover, two of the three living tree sites (67.90° N and 20.10° E; 68.20° N and 19.80° E) are far outside the network of subfossil sites. The FENN data can be downloaded via http://www.blogs.uni-mainz.de/fb09climatology/files/2012/03/Data.pdf.

2.2 Sampling sites

The tree-ring material originates from four different types of sampling sites: modern samples of living pines representing dry (inland) environments, lake riparian habitats, subfossil samples preserved in subaerial conditions and subfossils preserved in lacustrine sediments. It is notable that the subfossil material of TORN dataset originates merely from subaerial conditions (Bartholin and Karlén, 1983; Schweingruber et al., 1988). In other words, there is no subfossil material from lacustrine sediments included in the Swedish MXD data (Grudd, 2008). On the other hand, the FENN assemblage consists of subfossil samples collected at lakes only (Eronen et al., 2002). The modern part of FENN MXD data (from living trees) was produced by using tree-ring samples from only lake riparian sites (Esper et al., 2012).Thus, the principal difference between the TORN and FENN datasets stems from the studied habitat: the TORN data include dry sites whereas the FENN data is represented by lake shore environments.

2.3 Microdensitometry

X-ray based microdensitometry produces profiles of wood density through the radial segment of each sample tree. Each ring exhibits an annual density cycle where the wood of low density is formed during the early growing season (i.e., earlywood), with

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increasingly high densities towards the late summer and autumn (i.e., latewood). The intra-annual point where the density reaches highest value is taken as the maximum density (MXD) of that ring, whereas the consecutive values within the segment represent the individual MXD series. These series are of special interest in dendroclimatology because of their strong correlations with growing season temperatures as observed today broadly across the circumpolar boreal forests (Briffa et al., 2002).

Commonly, living trees are cored at breast height, and the increment cores exposed for microdensitometric analyses. Subfossil pinewood material can either be found as lying on dry grounds or as preserved in the sediment of small lakes. In the field, the unearthed logs are sawn into disks. Subsequently, in the workshop, radial laths are sawn perpendicular to the ring boundaries to be analysed using microdensitometry. It is important to note that even slight differences in the laboratory protocol during the X-ray process may profoundly alter the resulting MXD data (Grudd, 2008; Helama et al., 2010c, 2012). MXD data may become altered following the methods that are used to remove the wood extractives (organic, non-cell wall components) prior to analyses (Helama et al., 2010c), the wood moisture content during the measurement (Helama et al., 2012), and the radial step size of the density scanning (Grudd, 2008; Helama et al., 2012).

The two MXD datasets analysed here (TORN and FENN) were produced using different X-ray methods and data analysis. The TORN dataset consists of data produced in different decades and laboratories (Grudd, 2008; Melvin et al., 2013). It has been shown for TORN data that the old MXD values (Schweingruber et al., 1988) exhibit lower standard deviation of density variability than the MXD values produced using evolved technical property of the X-ray scanner (Grudd, 2008). In order to deal with this bias, Grudd (2008) reduced the variance in new MXD data to match with the old variance. More recently, Melvin et al. (2013) added more data into the TORN dataset. These data were produced in a different laboratory. Comparisons with the differently produced MXD data showed a need for additional adjustments for mean and standard deviation of the data because of the different laboratory protocols (Melvin et al., 2013).

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In this study, we are using these adjusted TORN data (S88G1112A.mxd data from (http://www.cru.uea.ac.uk/cru/papers/melvin2012holocene/).

2.4 Standardization methods

2.4.1 Regional curve standardization

Our analyses are based on Regional Curve Standardization (RCS) (Briffa et al., 1992, 1996; Briffa and Melvin, 2011) with the signal free implementations (Melvin and Briffa, 2008; Briffa and Melvin, 2011) and its correction (Matskovsky, 2011). In the original RCS technique presented by Briffa et al. (1992), the standardization curve is not fitted individually to each data of tree-ring series. Rather, the standardization curve is assumed to display regionally representative cambial (that is, biological and thus non-climatic) trend in the total tree-ring variability (Briffa et al., 1992, 1996). Therefore, this trend can be derived as a single mean curve (here, RC1) of the data aligned according to their cambial ages. The process of averaging the series reveals tree-ring variations common to their biological ages and the expected non-climatic component can be detected as the mean curve. Typical of conventional RCS method, this curve is assumed to be not affected by climate. Subsequent to averaging, the mean curve is commonly smoothed to reduce the effect of random fluctuations. Time-varying response smoothing (TVRS; Melvin et al., 2007) with the routine of Melvin et al. (2007: see their Appendix A) was used where SSY (spline stiffness for each year) equalled the cambial age in years plus 15 yr. We used a cubic spline with 50 % variance cut-off (Cook and Peters, 1981) on the frequency period of SSY-years. Using this method, the RCS is carried out with a single Regional Curve (referred hereafter as RC1) to standardize all tree-ring series and the tree-ring indices are derived as ratios between the observed tree-ring value and value expected by the RCS curve. This process is expected to remove a large portion of non-climatic variations presented in the initial series. Parts of each tree-ring series contributing to the Regional Curve over the weakly replicated old cambial ages (with replication less than 10) were removed before using the modified conventional RCS method.

2.4.2 Signal-free approach

The conventional RCS method can be combined with the signal-free (SF) approach (thus, RC1SF) as suggested by Briffa and Melvin (2011) and as already applied in several studies (Helama et al., 2010b; Björklund et al., 2013; Melvin et al., 2013; Cooper et al., 2013; Wilson et al., 2013). In contrast with conventional RCS, this method assumes that the estimate of standardization curve as just an average of all available series is *biased* by climate, because the initial tree-ring series themselves contain a significant climatic component. Thereby the mean curve may retain a large proportion of climatic influence, which becomes effectively removed from tree-ring indices because the growth component represented by the curve is removed from the initial series. As an alternative, a more non-climatic mean curve could be produced from signal-free series whose climatic signal is removed prior to estimation of the standardization curve. Following Melvin and Briffa (2008), the removal of the climatic variations is done through process where the initial tree-ring values, aligned by their calendar years, are first divided by the index values of the conventional RCS-chronology. The resulting SF-values are averaged, aligned by their cambial years, following the typical RC1 procedure (see above). The new mean curve is then removed from the initial tree-ring values to produce a new (RC1SF) chronology. The process is repeated until no improvement in chronology estimation is achieved (see Melvin and Briffa, 2008 for details).

2.4.3 Correction procedure

An improvement of the chronology estimation, subsequent to RCS and SF methods, was previously attained by applying a correction (C) method (thus, RC1SFC, Matskovsky, 2011). This method, RC1SFC, is a novel application of the RCS and SF methods, tailored for detection of pure low-frequency signal in tree-ring chronologies. The error in RC1SF chronology is assessed and subsequently extracted from the data in order to produce a RC1SFC chronology. Similarly to SF method, which assumes that the simple RC may be severely biased by unwanted (i.e., climatic) effects, the correction assumes the SF-RC may be still biased by sample inhomogeneity. These types of tree-ring variations originate from the non-uniform distribution of individual series in time and uncommon individual tree growth peculiarities (Matskovsky, 2011). This method consists of three steps: (1) build a chronology only from SF-curves (initial series without climatic signal and high-frequency variations), (2) estimate the sample error using this chronology, (3) subtract this error from the initial chronology, thus correcting it. See the detailed algorithm of the correction procedure in the supplementary information file.

2.4.4 Multiple-RCS method

Our forth type of standardization method calculates multiple RCS curves from the same dataset and uses them (instead of a single curve used in the RC1, RC1SF and RC1SFC methods) to remove the non-climatic variations (Briffa and Melvin, 2011; Melvin et al., 2013). Following the previous suggestions (Melvin et al., 2013), we used two regional curves that were built using the SF routine (thus, RC2SF) and its correction (thus, RC2SFC). The process of defining the multiple RCS curves started by calculating the mean of SF-series for the cambial ages 1–100 yr for each tree. These values were divided by the mean of the first 100 yr of a single RC1SF curve (created using all trees) to yield relative growth rate (sensu Briffa and Melvin, 2011) for MXD production of each tree. All trees were arranged by this relative growth rate and the full set of trees was accordingly divided into two equally large groups (in practice, one group was larger by one tree if the total number of series in that chronology was odd). The regional curve was produced for each group for detrending each MXD series in the corresponding group. Here again we truncated all the tree-ring series to achieve replication of at least 10 samples for every RC value and TVRS spline was used for smoothing of RC curve. Comparisons between the chronologies were carried out only for the parts of chronologies with replication of at least 6 series. Therefore, the common period was limited by replication of TORN dataset and was set to AD 542–2006.

2.5 Design of experiments

The five types of standardization methods were used for comparison under the assumptions that TORN and FENN datasets are proxies for mean summer temperature (JJA months) and that temperature is spatially homogenous for the whole region. Under these assumptions, improved correlation between any pair of differently standardized TORN and FENN chronologies demonstrates higher common (i.e. temperature) signal.

We compared five types of chronologies (RCS, RC1SF, RC1SFC, RC2SF and RC2SFC) for TORN and FENN datasets and also used low-pass filtered chronologies with N-year smoothing splines (Cook and Peters, 1981) to focus on low-frequency signals ($N = 50$, 100, 200 and 300 yr). Detailed comparison of low-frequency signals between the TORN and FENN datasets was carried out using their RC2SFC chronologies. We also used subsampled FENN data because of its higher replication. Subsampling was supposed to highlight any difference arising in the FENN dataset when artificially reduced to the sample depth of TORN dataset. For details of the subsampling algorithm see the Supplement.

2.6 Temperature reconstruction methods

While the FENN dataset is privileged by its greater sample size and replication over the common period (since ca. AD 700), the benefits of TORN data lie in its homogeneity and its stronger correlation to temperature. Both materials have their benefits and following their high overall correlativity, it was justified to combine the data into an enhanced MXD-based paleoclimate reconstruction. The temperature reconstruction was produced from a combination of TORN and FENN datasets (called FULL dataset). The FULL dataset includes 711 series and covers the period BC 216–AD 2010 (BC 48–AD

2010 with replication more than 5 series). We used AD 1802–2010 as the common period for comparisons between the MXD proxy and instrumental data (Klingbjer and Moberg, 2003). The data over the year AD 1815 (with missing instrumental data) was excluded from all the dendroclimatic comparisons. Common period of instrumental and MXD data was divided into two periods (AD 1802–1905 and AD 1906–2010) to be used as calibration and verification periods and vice versa for producing JJA temperature reconstruction from MXD chronology. We used the following commonly used statistics to assess the quality of the reconstruction: Pearson correlation coefficient (r), Coefficient of determination (r^2), Reduction of error (RE), Coefficient of error (CE) and Root mean square error (RMSE) (Cook et al., 1994). The statistics of r^2, r and RMSE were calculated for calibration, verification and common (1802–2010) period with instrumental data (note that CE is actually r^2 for verification period).

MXD based JJA temperatures were reconstructed using non-smoothed and smoothed variance adjustment and linear regression methods (Lee et al., 2007, details in the supplementary information file).

2.7 Uncertainty estimates for the reconstruction

The uncertainties of the reconstruction arising from three independent sources were estimated as follows:

1. The uncertainty of replication by the Regional Curve (RC): this type of uncertainty arises from the RC replication uncertainty that generally increases towards higher cambial ages. This uncertainty will affect the uncertainty of every MXD index, depending on its cambial age. Since we used two RCs, this type of uncertainty is also dependant of the RCs we used and hence by the mean MXD for the first 100 yr.

2. The uncertainty of replication by the mean chronology: this uncertainty provides the confidence interval of the average of all MXD indices for each calendar year (taking into account the uncertainty #1).

3. The uncertainty from calibration: the uncertainty accounts for the uncertainty of mean and variance (as we use mean and variance adjustment reconstruction technique) over the calibration period (taking into account uncertainty #1 and #2).

As the three types of uncertainties are assumed to be independent, the uncertainty that arises from each source can be derived by subtracting previous uncertainties on the same confidence level. For this reason, the results on Fig. 8 show relative values of all the three uncertainties. For details of uncertainty estimation, see the supplementary information file.

3 Results

3.1 Sample size replication

The FENN dataset contains 2–6 times more samples than the TORN dataset through the most part of the common period (Fig. 2a). The replication of TORN chronology remains below twenty samples over the subfossil period. The sample size variation over the past 200 yr is explained by the high number of core samples from living trees during this period. Over the twentieth century, the absolute increase of young pines is higher for FENN data in comparison to TORN data. However, the relative increase of young pines may be higher for the TORN dataset (Fig. 2a).

TORN and FENN full sample sets were split into trees with dense ("trees with good growth") and less dense ("trees with poor growth") MXD values. This nearly halves the replication in the resulting sub-chronologies through the study period (Fig. 2a). The visual inspection shows that the difference between the number of denser and less dense tree samples do not correlate between the FENN and TORN datasets ($r = -0.005$, Fig. 2b). The use of multiple-RCS is expected to eliminate the biases arising from temporal distribution of well and poorly growing trees (Melvin et al., 2013). Since the datasets originate from nearby regions, the described asynchrony indicates that the examined growth component (relative growth rate) is not related to low-frequency climate variability. Therefore we assume that this finding supports the use of multiple-RCS.

3.2 MXD chronologies

Subsequently, the initial MXD values were transformed into RC1, RC1SF, RC1SFC, RS2SF, RS2SFC indices using the corresponding standardization curves (Fig. 3a), and averaged into a corresponding set of mean MXD chronologies (Fig. 3b). The correlations between the differently standardized chronologies decline towards lower frequencies of growth variability (Table S1). On average, the non-smoothed chronologies agree with a mean correlation coefficient of $r = 0.660$, whereas the 50 yr, 100 yr, 200 yr and 300 yr smoothing results in mean correlation coefficients of $r = 0.516$, $r = 0.459$, $r = 0.421$ and $r = 0.444$, respectively. The observed tendency of lower correlativity at lower frequencies indicates the increasing uncertainties in estimating particularly the long-term temperature variations by MXD proxy data.

Invariably, the highest correlations between the chronologies of same standardization method were those obtained by RC1SFC procedure (Table S1), that is, using a single regional curve both with signal free and its correction implementations. This result becomes even more obvious for correlations calculated at lowest frequencies (Table S1). It becomes evident that the applied correction (C) subsequent to SF implementation improves the actual SF estimation, and in particular the estimation of the low-frequency tree-ring variations, as already suggested in the original methodological study (Matskovsky, 2011). Applying multiple-RCS technique (RC2SF and RC2SFC) produces an improvement of FENN chronologies, but not of TORN chronologies. This may be, at least in part, owing to a smaller sample size of the TORN dataset that may not be sufficient for robust estimation of multiple RCs. This may be the reason for highest correlations obtained between TORN-RC1SFC and FENN-RC2SFC on varying time-scales (Table S1).

Differently produced FENN and TORN chronologies show consistent but also bifurcating dendroclimatic signals (Fig. 3b). Apart from many common features with synchronously ameliorated and deteriorated growth periods, it is found that the FENN chronologies exhibit notably higher growth prior to AD 900 and during the 17th century. Regardless of the standardization method, the TORN chronologies indicate higher growth during the recent decades and an increasing towards the present-day (Fig. 3b).

Since the TORN dataset is characterized by lower sample replication through the common period (Fig. 2a), an experiment was performed to test whether the observed growth bifurcations (Fig. 3b) could be explained by this property. The FENN dataset was randomly subsampled to mimic the TORN replication (Fig. 4a). We found that the difference in sample replication between the two datasets was not likely a reason for the deviating MXD fluctuations in FENN and TORN. Instead, the TORN chronology exhibits lower growth between the years 600 and 950, and 1600 and 1700, and higher growth since 1950s (Fig. 4b).

The low-frequency fluctuations could be detailed in the context of oscillatory modes dominating the multi-decadal to centennial MXD variations of FENN and TORN data (Fig. 5). Both chronologies showed nearly identical 54–56 yr and 67–70 yr periodicities, as well as precisely identical 113 and 133 periodicities. However, the TORN chronology was also characterized by the 33 yr, 244 yr and 488 yr periodicities, whereas the FENN chronology exhibited an additional sub-centennial oscillation of 86 yr periodicity (Fig. 5).

3.3 Climate-proxy comparisons

Comparisons between the chronologies and instrumental climate records (Fig. 6) demonstrate that both chronologies correlate with summer temperatures with a range of coefficients $r = 0.76$–0.79 (Table S2). At low frequencies, however, the correlations are higher when using TORN chronologies than with FENN chronologies ($r = 0.95$ and $r = 0.80$, respectively). This is not an issue of standardization method since the dendroclimatic correlations are invariably higher in the case of TORN, regardless of the used method (Table S2). Rather, the FENN chronologies show warming during the period 1802–1815 when the TORN and instrumental data indicate cooling (Fig. 7). Moreover, the FENN chronologies underestimate temperature around 1900 and since the 1950s.

In addition, normalized FENN chronologies show inflated values relative to TORN and instrumental record z-scores during the early twentieth century warming that occurred in the region in the course of the 1920s and 1930s (Fig. 7).

The FULL chronologies show even higher correlations with instrumental temperatures than TORN chronologies, the highest after multiple RCs and signal-free implementation with $r_{\mathrm{FULL-RC2SF}} = 0.795$ and $r_{\mathrm{FULL-RC2SFC}} = 0.793$ (Table S2). Here, the FULL-RC2SFC chronology was used for reconstructing the JJA temperature because it was indicated (Sect. 3.2, Table S1) that correction procedure improves proxy quality on longer timescales.

3.4 Summer temperature reconstruction

Our new temperature reconstruction is shown with three separate types of uncertainties since 216 BC (Fig. 8). Clearly, the uncertainties arising from MXD data are considerably narrower than the climate-proxy calibration uncertainty (uncertainty #3), especially over the past thirteen centuries. Over the earlier times, the uncertainties of the MXD data increase, consistently with the decrease in the sample replication (Fig. 2a). At low frequencies, the Common Era of the reconstruction is governed by the warm climatic phases culminating in the tenth and twentieth centuries. The peak temperatures during these periods are comparable with each other, whereas the warmth of the first century BC shows slightly higher temperatures. Nevertheless, the temporal length of the medieval warmth from the eighth to eleventh centuries overshadows the two other warm periods. The coolest climatic phases prevailed during the sixth and seventh, as well as the 13th through 19th centuries, the latter overlapping with the timing of the Little Ice Age. The warmest and coolest 30 yr periods occurred 31–1 BC and AD 536–565, respectively, when JJA temperatures averaged 15.3 and 12.7 °C, translating into maximal multidecadal temperature amplitude of 2.6 °C. The reconstruction exhibits periodic oscillations distinctly on multi-decadal (55 to 66 yr), centennial (86 to 129 yr), multi-centennial (257 to 515 yr), and millennial (1029 yr) time-scales (Fig. 9).

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4 Discussion

4.1 Comparison of datasets

Focusing on low-frequency fluctuations, the TORN (Schweingruber et al., 1988; Grudd, 2008; Melvin et al., 2013) and FENN (Esper et al., 2012) datasets show several common anomalies of synchronously high and low MXD values, as well as several common periodicities. Despite high correlation with summer temperatures and overlapping provenance of the original tree-ring material, the MXD data do not show consistent growth variations through the study period. The most obvious periods with the bifurcating dendroclimatic fluctuations occurred in the 7th, 9th, 17th and 20th centuries (Fig. 3b). Yet, the results from spectral analysis indicate disparate dendroclimatic signals in the form of significant oscillatory modes (Fig. 5). It is reasonable to argue that these dissociations likely represent MXD variations not closely related to climatic signal. Therefore, before interpreting the obtained paleoclimate information of the summer temperatures, it may be useful to discuss any possible reason behind the described inconsistencies of the two data.

Samples for the two chronologies originate from adjacent and partially overlapping geographical settings in northern Fennoscandia and we suggest that results showing diverging MXD fluctuations between the chronologies are not driven by spatial anomalies in regional climate. Indeed, one dissenting result was identified for the late twentieth century when both datasets contain tree-ring materials from living trees of the same (Torneträsk) region and thus for the period of supposedly enhanced homogeneity of provenance. Instead of climate, there are six likely sources of heterogeneity: (i) data quantity, (ii) biogeographical differences of source materials, (iii) varying microdensitometric and (iv) tree-ring standardization methods, (v) cambial age structure of the chronology, (vi) habitat of riparian and inland pines.

4.1.1 Data quantity

Data quantity is a factor that distinctly divides the original tree-ring materials for chronologies with high (FENN) and low (TORN) replications (Fig. 2a). The sample replication and the law of large numbers should not be overlooked in the course of any dendrochronological procedure (Fritts and Swetnam, 1989). Moreover, it may be generally comfortable to rely on massive sample replication in dendrochronology (Büntgen et al., 2012). Subsampling of the more deeply replicated dataset (FENN) revealed, however, that the diverging MXD fluctuations could not be reproduced by randomly reducing the quantity of that dataset (Fig. 4b). Thus, we argue that the data quantity may not be a primary factor producing the differences as observed between the TORN and FENN chronologies.

4.1.2 Biogeographical aspects

The primary difference between the TORN and FENN datasets stems from their spatial characteristics (Fig. 1). While the TORN has been collected from a restricted locality of Torneträsk in northernmost Sweden (Bartholin and Karlén, 1983; Schweingruber et al., 1988; Grudd, 2008), the subfossil sampling sites of FENN are spread over the northern Finnish Lapland (Eronen et al., 2002). Two of the three modern FENN sites originate from northern Sweden, including Torneträsk (Esper et al., 2012). Despite of this proximity of modern sampling sites of the two collections, the two chronologies indeed diverged intriguingly after AD 1950 with notably higher growth as observed for the TORN chronologies (Fig. 7). Since the tree-ring material of FENN and TORN for this period comes from neighbouring sites, it must not be the biogeographical aspects which play a crucial role in the observed divergence. It is interesting, however, that the preceding periods of divergence (during the 7th, 9th and 17th centuries) showed an opposed mismatch (in respect to the 20th century) where the FENN chronologies come with higher growth. In biogeographical context, the MXD may not be insensitive to stand density variations, as shown by thinning experiments. These studies indicate that

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the *P. sylvestris* latewood density (pertaining to MXD) increases substantially following stand thinning (Peltola et al., 2007). Likewise, it is known that the studied sites have experienced major changes in their natural stand densities over the past millennia with highest overall stand density during the MWP (Helama et al., 2005, 2010a). Thus, past fluctuations in stand density may at least hypothetically explain the diverging MXD chronologies.

4.1.3 Microdensitometry

Varying microdensitometric methods have previously shown to produce significantly altered MXD data (Helama et al., 2010c, 2012). Indeed, the initial materials of the two datasets were produced in different laboratories and in the course of the quarter of a century. In fact, Grudd (2008) described this development in the context of the X-ray microdensitometry sensor width. In particular, the sophistication of the device results in data with higher MXD standard deviations (Grudd, 2008). The variance of the new data was adjusted to expected variance by the old data (Grudd, 2008) and here we have used similarly rescaled (Melvin et al., 2013) MXD data only. Although such adjustment of the initial data is a logical approach to solve the problem of differently produced MXD data, the issue may be too complex to be surmounted by linear scaling of the initial data. A change in laboratory measurement protocol may change the amplitude (as measured by standard deviation) and the autocorrelation of the MXD series (Helama et al., 2010c, 2012). Rescaling of tree-ring series with dissimilar autocorrelation structures may distort particularly their low-frequency band of variations (Helama et al., 2009a). The calibration of the differently produced MXD data may introduce, at least hypothetically, additional level of uncertainty for the MXD values.

4.1.4 Tree-ring standardization

Tree-ring standardization is generally understood as an obstacle for deriving the low-frequency climate information from tree-ring proxies. Many standardization methods

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are indeed incapable of retaining the long-term and -period growth variations (Cook et al., 1995). As a consequence, tree-rings have even become notoriously poor indicators of low-frequency climate variability for wider readership (e.g. Broecker, 2001). Recent decade has however undergone a methodological development of the standardization. Several methods (Helama et al., 2005; Nicault et al., 2010; Briffa and Melvin, 2011; Matskovsky, 2011; Melvin et al., 2013) have evolved from the simple RCS method (Briffa et al., 1992) for improved low-frequency preservation. Interestingly, the RCS method has been applied in the study region for *P. sylvestris* tree-ring data already in the 1930s (Erlandsson, 1936) whereas the subsequent studies have used the data of same species and region for systematic comparisons between RCS and other methods of standardization (Briffa et al., 1992, 1996; Cook and Briffa, 1990; Helama et al., 2004). In the same context, Esper et al. (2012) showed that the RCS preserves, if such growth properties underlie the initial data, even multi-millennial long-term trends in the resulting MXD chronologies. Similarly, our results indicate that the preservation of the low-frequency variations is not an issue that could have caused the observed differences between TORN and FENN chronologies. This statement is in accordance with the results showing evidence for similar divergences between the chronologies regardless of the varying (RCS) standardization method (Fig. 3b). That is, the 7th, 9th, 17th and 20th century bifurcations remain as the most notable differences between the TORN and FENN chronologies.

In the context of standardization, our results provided several other implications. Regarding the correction procedure, it was found that the dendroclimatic correlations of FENN-RC1SFC were notably higher in comparison to FENN-RC1SF. That is, the correction procedure improved the value of that MXD dataset as a summer temperature proxy. Likely, this improvement arises from the very non-uniform age structure of the same dataset over the last two centuries, with increase of young trees (younger than 100 yr). This is how the correction procedure significantly reduces the "sample error" due to uneven age distribution over the AD 1950–1990 period (see Fig. 7). Nevertheless the correction procedure may not always improve the proxy on short timescales,

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as could be implied over the instrumental period (Table S2). In fact, the correction procedure was designed for amplification of the low-frequency climate signal in tree-ring proxies, and its performance may not be evident on short terms. Indeed, the correction showed its advantages in improving the quality of chronologies on long timescales (Table S1). Nevertheless, its further investigation on extended datasets from different forest types is recommended.

The benefits of using multiple RCs may be limited by the size of dataset, as outlined above (Sect. 3.2). This deduction is supported as the use of multiple RCS provides improved correlations with more densely replicated FENN dataset but not with smaller TORN dataset (Table S1). Interestingly, when TORN replication is enhanced by living trees, the multiple-RCS (TORN-RC2SF) chronology does show higher correlations with instrumental record (Table S2). Consistently, the dendroclimatic correlations improve with multiple-RCS in the case of FENN and FULL datasets. Moreover, the correction procedure failed to improve the TORN-RC2SF (see Table S1 for 100, 200 and 300 yr smoothing). We assume this to be a consequence of reducing the quality of TORN-RC2SF chronology via the use of multiple RCs in the case of less well replicated TORN dataset.

4.1.5 Cambial age structure

As previously alluded to, the TORN and FENN chronologies deviate notably over the last half of the twentieth century when the age structure diverges with a more pronounced addition of MXD series of young pines to FENN dataset. Obviously, the cambial age structure of the chronology could serve as a specific factor explaining the observed MXD bifurcation. However, the coherence of long-term MXD variations between different age classes was generally provided by Esper et al. (2012). Yet, the analysis of Melvin et al. (2013) showed that their young pines (TORN) come with higher MXD values particularly over the late twentieth century. These lines of evidence let us assume that the increase of young pines in the FENN dataset over this period could not result in lowered MXD values, in comparison to TORN data. A more detailed investigation

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for age-dependent growth variations is recommended to clarify the influence of young pine MXD series for estimating the mean chronology.

4.1.6 Riparian and inland habitats

It is essential to note that the initial tree-ring materials originate from predominantly dry inland (TORN) and lake riparian (FENN) habitats. With these regards, the subfossil period of the chronologies is covered with snags from subaerial conditions (TORN) and sub-aquatic stems recovered from lake sedimentary archives (FENN) (Bartholin and Karlén, 1983; Schweingruber et al., 1988; Eronen et al., 2002; Grudd, 2008; Esper et al., 2012). In the study region, the riparian *P. sylvestris* are expected to experience less drought stress and, in fact, do exhibit a stronger dendroclimatic response in their tree-ring widths to summer temperatures (Hundhausen, 2004). These findings are contrasted by our MXD results showing that actually the TORN chronologies of inland habitats demonstrate appreciably higher correlations with summer temperature than the FENN chronologies of riparian habitats (Table S2). Secondly, a previous comparison using tree-ring material from living pines of riparian and inland habitats showed notably higher MXD indices from riparian trees, in comparison to pines growing in inland conditions (Esper et al., 2012). However, the inland TORN chronologies showed higher MXD values over the twentieth century, in better accordance with instrumental temperature data than the riparian FENN chronologies (Fig. 7). Parallel observation was previously derived for *P. sylvestris* tree-ring widths in Central Scandinavian Mountains where their wet-site chronology explained considerably less (24 %) instrumental climate variance than the dry-site (43 %) chronology (Linderholm, 2001). While this set of results demonstrate a clear moisture insensitivity of MXD data in the studied setting of inland stands, the potential role of waterlogging, that has been seen as probably the primary restriction on the radial growth of *P. sylvestris* on wet sites (Moir et al., 2011), may remain as a factor leading to noisier MXD variations in the FENN data (Fig. 7).

Also the spectra of the TORN and FENN chronologies differed (Fig. 5). While the 56, 67, 113 and 133 yr periodicities in TORN agreed reasonably with the 54, 70, 113 and

133 yr periodicities in FENN data, only the TORN chronology exhibited a 33 yr periodicity whereas the FENN chronology showed a solitary periodicity of 86 yr. Similarly, a disparity of periodicities in *P. sylvestris* tree-ring widths was detected in Central Scandinavian Mountains where the dry-site and wet-site chronologies displayed periodicities of 66 yr and 19 yr respectively (Linderholm, 2001). With these regards, the spectral analysis would in fact imply differentiated low-frequency variations in the studied inland and riparian MXD data.

A list of at least four conceivable factors having caused the described MXD divergences could include (1) the past changes in stand density that could have altered the MXD growth disproportionally near the timberline (i.e., TORN habitats) and in more southern sites (i.e., FENN), (2) the inclusion of young pines and their MXD values for chronology estimation, (3) the calibration of differently produced MXD data into combined record, and, (4) the potential role of waterlogging which may have occasionally restricted the MXD production on wet sites. Detailed investigations on these issues are too far beyond the scope of this study. Instead, we urge the future research to delve into the roles of the three aforementioned factors in producing the MXD variations in relevant biogeographical settings.

4.2 Low-frequency temperature variations

Over the Common Era, the reconstruction (Fig. 8) exhibits consistency with the climatic phases through the MWP and LIA (Lamb, 1977). Thus, the reconstruction is similar to previous investigations using *P. sylvestris* tree-ring widths and MXD as proxies of Fennoscandian past temperature variability (Briffa et al., 1992, 1996; Grudd, 2008; Helama et al., 2009a, 2009c; Esper et al., 2012; McCarroll et al., 2013; Melvin et al., 2013). Moreover, the reconstruction agrees with the previous studies showing evidence of comparatively similar warmth during the MWP and the most modern decades (Briffa et al., 1992; Grudd et al., 2002; Helama et al., 2009a, c; McCarroll et al., 2013; Melvin et al., 2013). Even warmer times were experienced during the first BC and AD centuries (Esper et al., 2012). These are also the times when the uncertainty envelope of

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the reconstruction becomes wider. The widening yields especially from the decreased sample replication over the earlier period (Fig. 8 and Fig. 2a). Nevertheless, the long duration of the MWP makes it incomparable to the twentieth century warmth. As an interesting feature of the reconstruction, the start of the MWP appears as early as the 8th century, lasting until the end of the 11th century, whereas the widespread positive temperature anomalies in the Northern Hemisphere are observed from the 9th to 11th centuries (Ljungqvist et al., 2012).

Apart from these millennial temperature variations, the reconstruction displays periodicities on multi-decadal, centennial, and multi-centennial time-scales (Fig. 9). In Fennoscandia, the tree-ring variations of similar multi-decadal (53 to 66 yr) scales have previously been linked (Linderholm, 2001; Helama et al., 2009a) to variations in sea surface temperatures of the North Atlantic Ocean (Schlesinger and Ramankutty, 1994). Likewise, the century-scale variations (80 to 120 yr) in the regional tree-ring based temperature reconstructions have been attributed to the Gleissberg (de Jager, 2005) cycle of solar activity (Briffa and Schweingruber, 1992; Ogurtsov et al., 2001). Spectral densities between 250 yr and 350 yr are common to temperature histories from the Greenland ice cores, North Atlantic and the Torneträsk tree-ring widths (Sejrup et al., 2011) but their possible origins may remain uncertain. Longer scale variations (500 to 1000 yr) may be indicative of North Atlantic circulation patterns (Chapman and Shackleton, 2000).

Actually, the North Atlantic influence could be expected to drive a notable part of the natural climate variability in the studies sites. The region is directly downwind of the Atlantic Ocean where the air pressure patterns, especially the North Atlantic Oscillation (NAO), impact the regional temperature as well as precipitation variations on synoptic scales (Hurrell, 1995). Apart from the instrumentally observed variations, the NAO has been shown to exhibit centennial fluctuations with pervasively positive and negative phases during the MWP and LIA (Trouet et al., 2009; Mann et al., 2009). In fact, the NAO-sensitivity of the climate has been described near the study region using several multi-proxy datasets through the MWP and LIA, showing seasonal variations in winter

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(warmer and moister) and summer (cooler and less rainy) climate, in accordance with the expected NAO-influence (Helama et al., 2009b; Luoto and Helama, 2010; Helama and Holopainen, 2012; Luoto et al., 2013; Nevalainen et al., 2013). Moreover, the temperature variations through the MWP and LIA could be linked with the periods of more and less intensive phases in the formation of North Atlantic deep-water (Helama et al., 2009c).

5 Conclusions

We have taken advantages of two well-known tree-ring datasets, the Torneträsk MXD chronology in northern Sweden, and the newly constructed Fennoscandian MXD chronology to develop a new MXD-based temperature reconstruction that preserves the low-frequency variability. We applied RCS based novel standardization techniques and also, for the first time for these datasets, represented uncertainties emerging from different sources and explored the potential sources of noise in these datasets. The reconstruction provides a valuable proxy for exploring the past climate variability in the high-latitudes of Europe. Existence of some noise does become obvious as the two chronologies deviate over the instrumental period as well as over their late Holocene common period. Although the MXD records have been used regularly for palaeoclimate reconstruction both in the study region and elsewhere, and despite of the past efforts to understand the MXD behaviour over time and space, our results suggest that particularly the low-frequency band of MXD variations may contain a proportion of tree growth variations unrelated to actual temperature history. Based on these findings, we have identified several additional issues that dendroclimatic research could emphasize in more details to gather more advanced understanding of potential pitfalls while using high-latitude MXD data for palaeoclimate temperature reconstructions: (1) influence of past population density variations on MXD data, (2) potential biases when calibrating differently produced MXD data to produce one proxy record, (3) influence of young pine MXD data over the most recent past, and (4) possible role of waterlogging on MXD production when analysing tree-ring data of riparian trees. Our experiments have showed that application of novel standardization techniques can reduce unwanted biases connected to these pitfalls. Thus our new reconstruction can be used as the source of information about year-to-year, as well as centennial and longer variations of summer temperature in Northern Fennoscandia for the Common Era. Nevertheless, the use of other proxies that can reproduce low-frequency past temperature variations is highly preferable in every paleoclimatic study.

Supplementary material related to this article is available online at http://www.clim-past-discuss.net/9/5659/2013/cpd-9-5659-2013-supplement.pdf.

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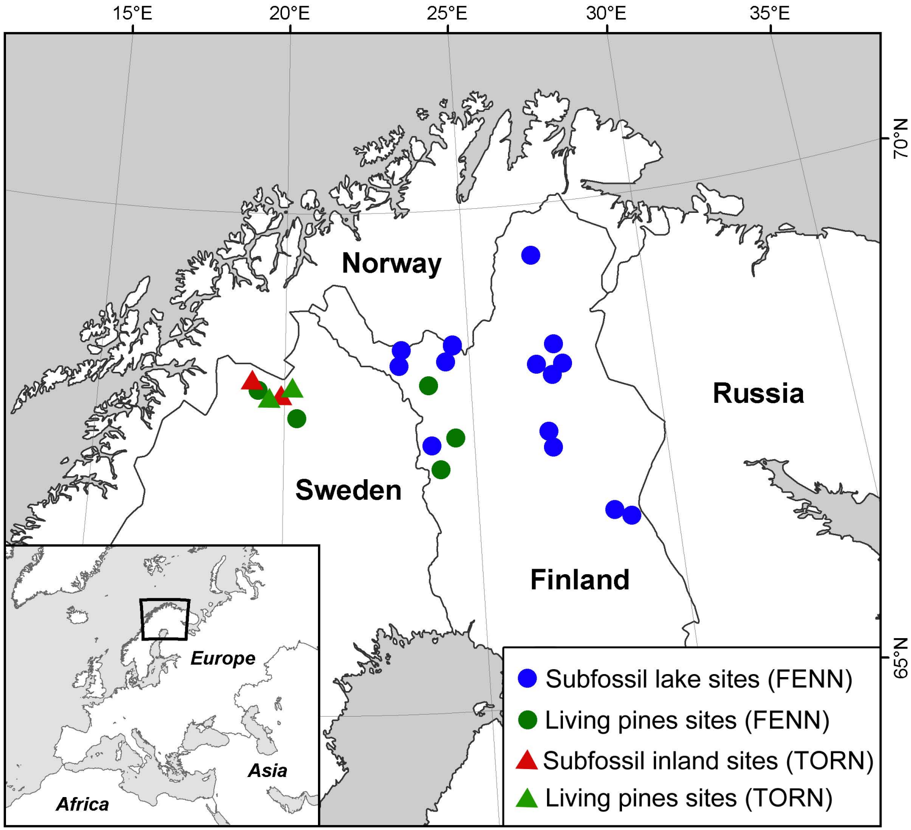

Fig. 1. Subfossil and living pines sites location for FENN and TORN datasets.

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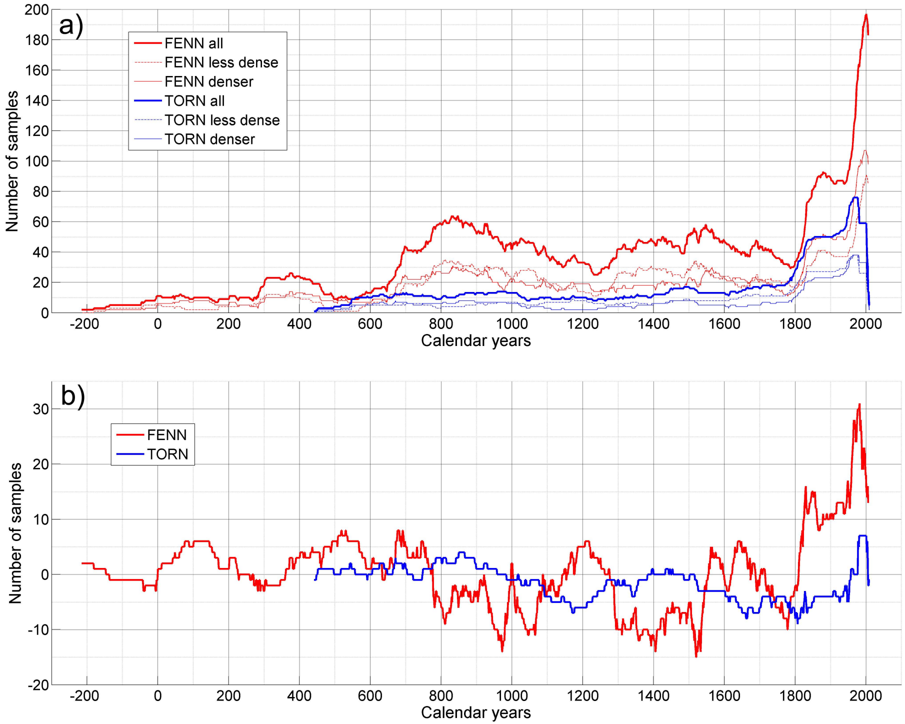

Fig. 2. Sample replication for FENN and TORN full datasets, denser and less dense cohorts (trees with higher and lower average MXD values for the first 100 yr) **(a)** and difference between replications of denser and less dense cohorts for TORN and FENN datasets **(b)**.

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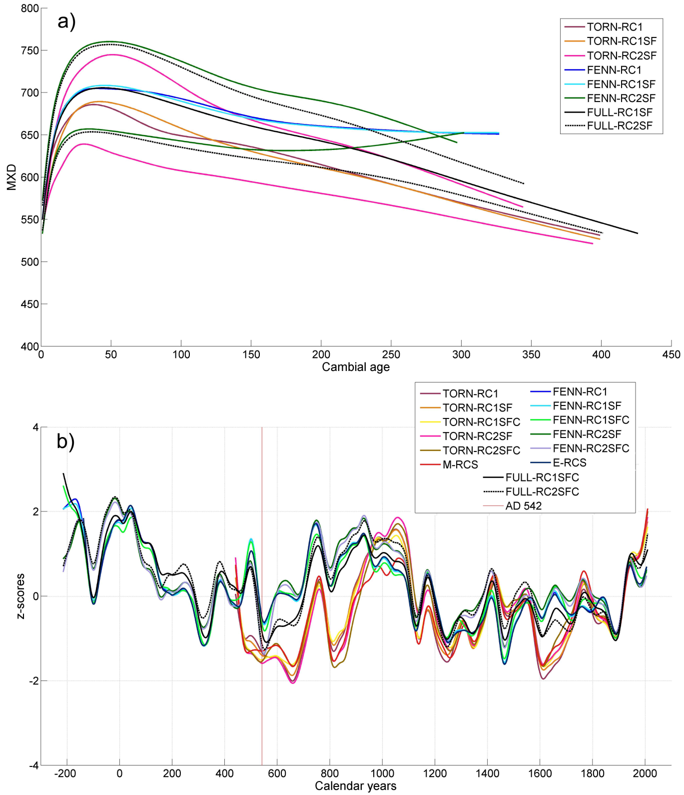

Fig. 3. Regional curves **(a)** and chronologies **(b)** for TORN, FENN and FULL datasets and different types of standardization. All the chronologies are smoothed with 100 yr splines. Variance and mean standardized to the period AD 1802–2006, 15 yr smoothed data is used for variance adjustment.

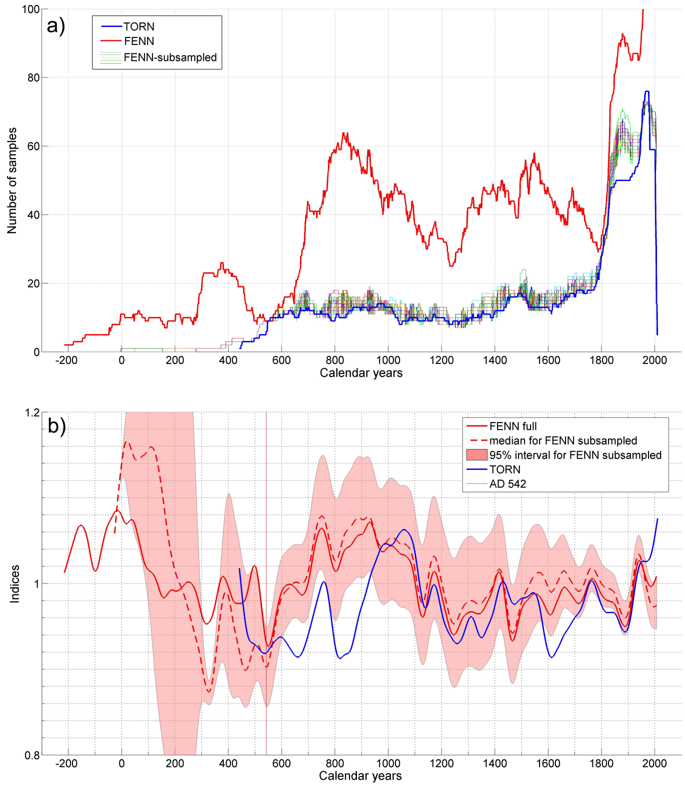

Fig. 4. Replication of TORN, FENN and subsampled FENN datasets **(a)** and comparison of RC2SFC chronologies for different datasets **(b)**. Red shading shows the area between 2.5th and 97.5th percentiles for FENN subsampled datasets. Vertical red line shows threshold for well-replicated datasets (more than 5 series). All series smoothed with 100 yr splines. Variance and mean standardized to the period AD 1802–2006, 15 yr smoothed data is used for variance adjustment.

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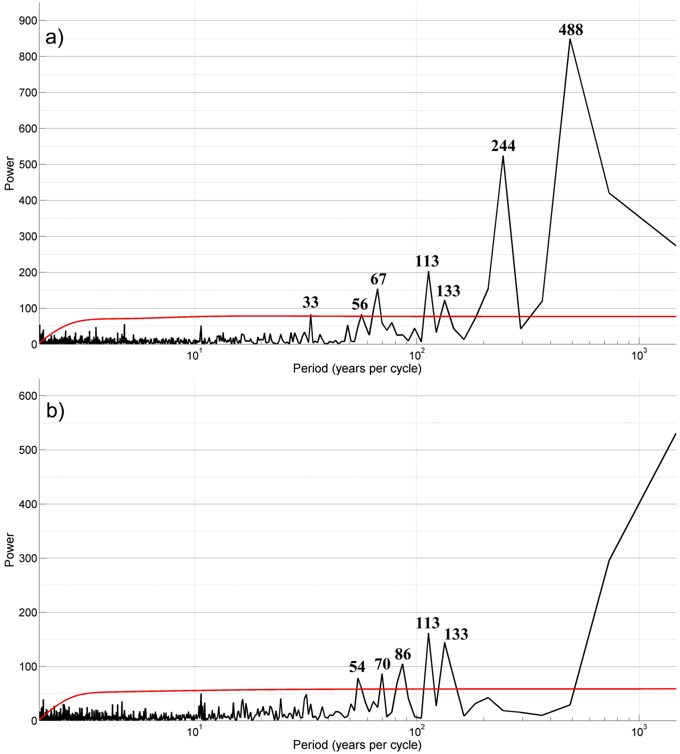

Fig. 5. TORN-RC1SFC **(a)** and FENN-RC2SFC **(b)** spectrum. Red line shows power spectrum of red noise with lag 1 autocorrelation estimated from the series. Period – AD 542–2006.

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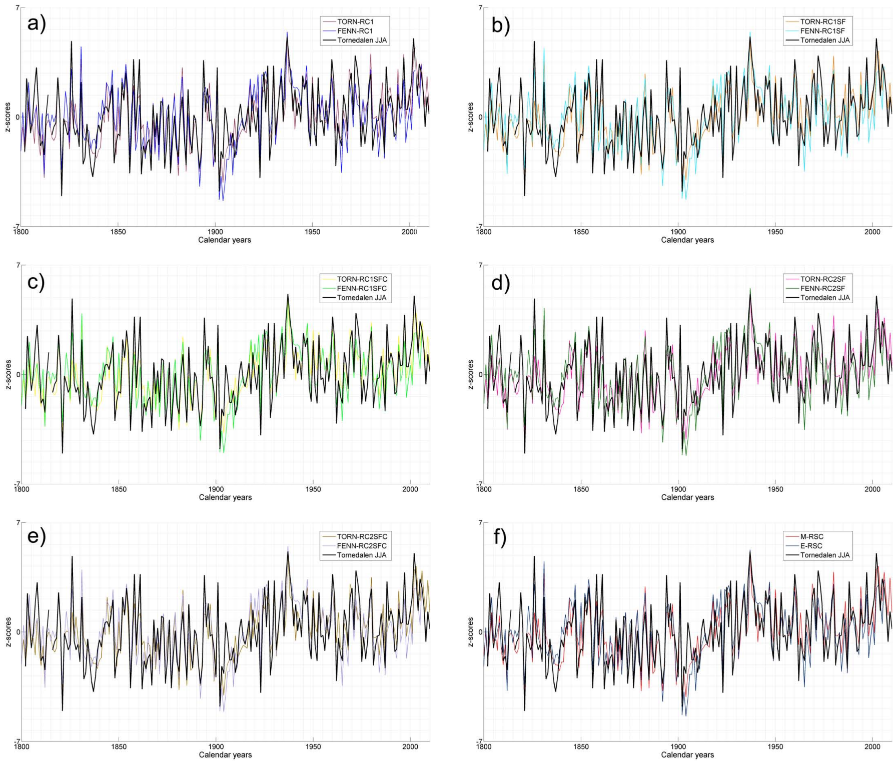

Fig. 6. Tornedalen JJA temperatures (black) and TORN and FENN chronologies (colors like on the Fig. 2) **(a)** RC1 **(b)** RC1SF **(c)** RC1SFC **(d)** RC2SF **(e)** RC2SFC **(f)** M-RCS and E-RCS. Variance and mean adjusted to AD 1802–2006 using 15 yr smoothed data.

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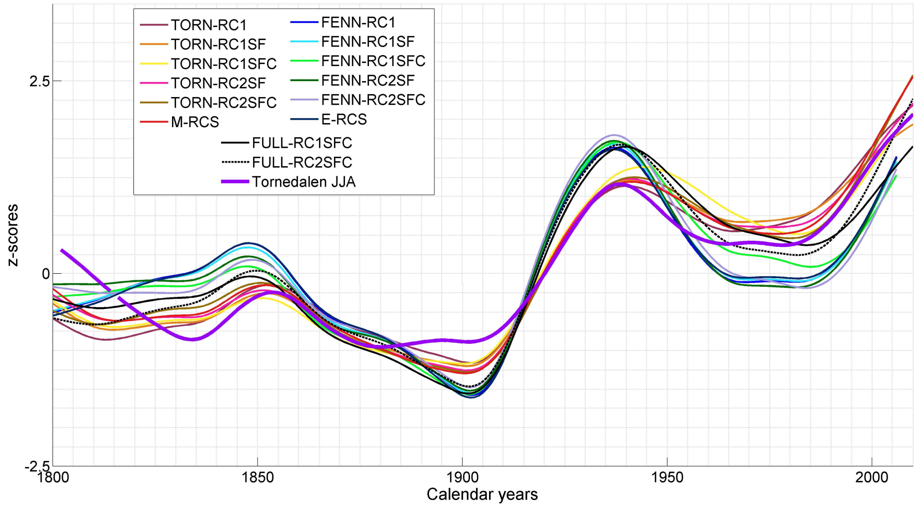

Fig. 7. TORN, FENN and FULL chronologies with Tornedalen JJA temperatures. Variance and mean adjusted to AD 1802–2006 using 15 yr smoothed data. All the data smoothed with 50 yr splines.

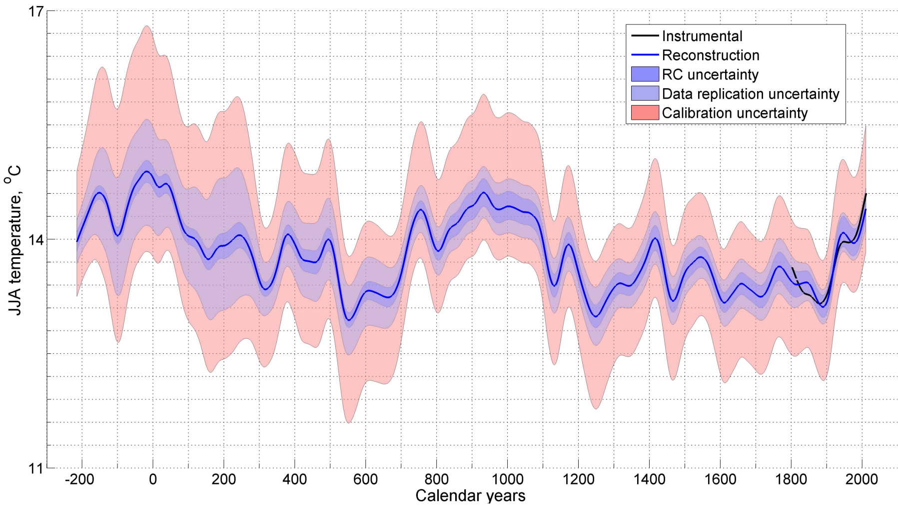

Fig. 8. Reconstruction of JJA temperatures with 95 % uncertainty intervals. See text for details. Values are smoothed with 100 yr splines.

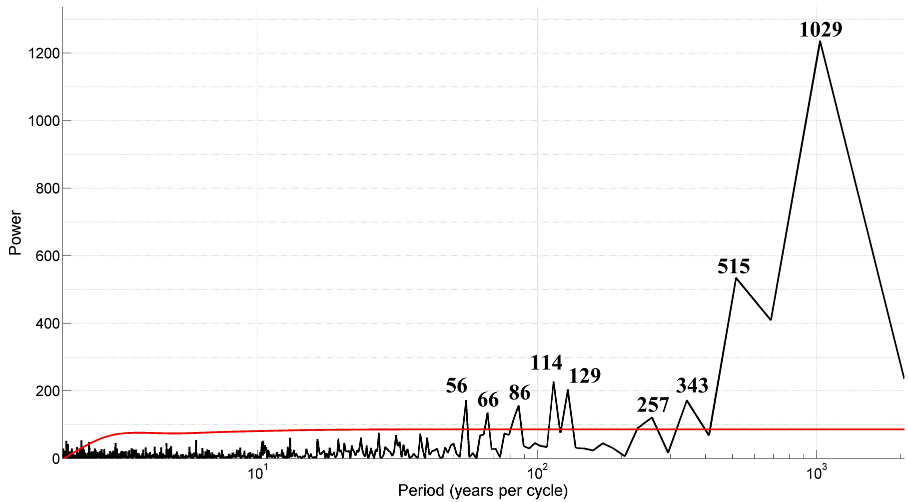

Fig. 9. Fourier analysis for FULL-RC2SFC. Red line shows power spectrum of red noise with lag 1 autocorrelation estimated from the series. Period – BC 47–AD 2010.

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