Dear Editor,

The manuscript (No.: cp-2015-4) entitled '1200 years of warm-season temperature variability in central Scandinavia inferred from tree-ring density' has been revised.

The revision is based on the last revised manuscript. We thank the two reviewers for their comments. We are also grateful for your encouragement during the revision processes. All comments have been considered when revising the manuscript. The point-to-point responses to the comments are listed below.

Response to reviewer #3

1. I need to recommend another thorough language check. There are less but yet numerous spelling mistakes in the manuscript.

Re: We have checked the spelling carefully and consulted a native English speaker colleague who went through the revised text once again.

2. The application of the "mean-adjustment" among sub-sites is still not fully convincing to me. The new supplementary figures that address the initial criticism do not disperse my doubts. In fact the figures confirm that the dataset lacks two prerequisites: Mean age in the reference period differs considerably among sub-sites and most sub-sites do not cover what is called the "common period". As indicated in my original remarks both conditions can induce an offset in the mean MXD-values, which is spuriously suppressed by adjusting the mean. Possibly, these effects are small, but this would have to be proven first! There are many tree-ring datasets out there which are a combination of nearby sub-sites and some of them could potentially be treated with a "mean-adjustment". But before advocating this new method, these issues should be sorted out.

Re: We agree with the point that the similar mean age and the sufficient overlap among sub-sites are important for the application of the mean adjustment method. We have emphasised the importance of these prerequisites in section 2.2 and 3.2.

In our dataset, the samples at different sub-sites do not exactly cover the same common period. For some samples, only a part of the samples share the common period. To alleviate this shortage, when adjusting mean values, only the part of a sample covering the common period was used to compare with the reference mean value when calculating the adjusted value for each sub-site. In the previous study (Zhang et al., 2015) we found that the differences in mean absolute MXD values among the sites of different elevations in a given period were larger than among the sites of similar elevation between MCA and LIA'. Therefore, we argue that the slight-mismatch of the time-spans within the common periods among the sub-sites should not bias the mean-adjustment. This statement has been added to section 2.2.

As suggested by the reviewer, we also checked the mean age of the samples in each sub-site to show that this is not going to be a substantial biasing factor. During the

“common period” of 1300-1550, the mean age of samples at the reference site (Furuberget-north) is 105 years, Håckervalen-south: 101 years, Ö Helgtjärnen: 90 years, Lilla-Rörtjärnen: 86 years, Jens Perstjärnen: 153 years. During the “common period” of 1107-1291, the reference sites mean age is 70 years and for Bodsjö: 79 years. This shows that the mean ages of most of the sites at these “common periods” do not deviate substantially from each other (the mean ages represents mature trees, and not juvenile or old aged trees, which can be said to deviate in mean values just because of age). From Fig. S2a, we can see that the difference of the MXD values at this age range is much smaller than the difference caused by the elevation/local-environment (see also the adjusted values in Table 1). Therefore, we argue that mean-adjustment should not be biased by tree age in these sample materials. A table has been added to the supplementary. We also add this statement to section 2.2.

3. The discussion was largely revised. It is now more focused on the new findings of this story. Unfortunately, the authors are often too vague and thus some of their conclusions appear somewhat bold. One such example is that two reconstructions are referred to as “rather similar” (rather subjective term!) in line 248, although exchanging the records would certainly alter the results and maybe their interpretation (Figure 6 indicates a different timing for some of the cold and warm extremes identified in panel d if using the RCS- instead of the RSFi-reconstruction). The discussion could also gain conciseness if the authors would follow more closely their line of argument, for example regarding their broad discussion about potential causes for the MCA (lines 254-271) which seems pretty misplaced.

Re: We have changed the relevant parts of the discussion and the conclusion according to the reviewer’s comments. Specifically, we have changed the statement of ‘rather similar’ to ‘similar at multi-decadal timescale’; we also added the information of the timing for the cold and warm extremes identified based on the 2-curve RCS standardized chronology in the discussion, and changed the relevant statements regarding the extreme timing in the conclusion; we removed the discussion about the potential causes for the MCA.

We believe that we have appropriately addressed all the reviewer’s concerns in the revised manuscript.

Sincerely,

Peng Zhang on behalf of all co-authors

References

Zhang, P., Björklund, J., and Linderholm, H. W.: The influence of elevational differences in absolute maximum density values on regional climate reconstructions, Trees, 29(4), 1259–1271, 2015.

1200 years of warm-season temperature variability in central Scandinavia inferred from tree-ring density

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Abstract

Despite the emergence of new high-resolution temperature reconstructions around the world, only a few cover the Medieval Climate Anomaly (MCA). ~~Improved understanding of the spatiotemporal characteristics of the MCA is important in terms of understanding how local temperatures keep a high level under natural forcing conditions.~~ Here we present C-Scan, a new Scots pine tree-ring density based reconstruction of warm-season (April–-September) ~~temperature~~temperatures for central Scandinavia~~, called C-Scan,~~ back to 850 CE, extending the previous ~~one~~reconstruction by 250 years. C-Scan is ~~largely~~ based on ~~pine trees~~samples collected in a confined mountain region, ~~where the samples were~~ adjusted for their differences in altitude and local environment, and standardised ~~in order~~using the new RSFi algorithm to preserve ~~as much mid- and long-term temperature change as possible.~~low-frequency signals. In C-Scan ~~suggests that,~~ the warm peak of MCA ~~occurred in~~occurs ca. 1000–-1100 CE, and ~~points to a~~the Little Ice Age (LIA) between 1550 and 1900 CE. Moreover, during the ~~past~~last millennium the coldest decades ~~were~~are found around 1600 CE, and the warmest 10~~,~~, and 30 ~~and 100~~ years ~~occurred~~occur in the most recent century. By comparing C-Scan with other millennium-long temperature reconstructions from Fennoscandia, regional differences in multi-decadal temperature variability, especially during the warm period of the last millennium ~~were~~are revealed. Although these differences could be due to methodological reasons, they may indicate asynchronous warming patterns across Fennoscandia. Further investigation of these regional differences and the reasons/mechanisms behind them are needed.

Key words: Central Scandinavia, Last millennium, Maximum ~~late wood~~latewood density, Scots pine, Warm-season temperature

1. Introduction

In order to assess the role of human activities ~~on the~~in current climate change (Bindoff et al., 2013), numerous efforts have been made to ~~put~~place the present warming in a ~~long~~longer-term context (e.g.~~.,~~, Wilson et al., 2016). Despite these attempts, there are still ~~some~~ controversies about past climate. For example, present-day global mean ~~temperature~~ air temperatures may have been ~~as~~ equally-high ~~as in the present~~ around one thousand years ago~~,~~ during the so-called Medieval Climate Anomaly (MCA; Lamb, 1969; Grove and Switsur, 1994). However, ~~this has been questioned~~ since regional temperature reconstructions display large variability in the timing ~~as well as~~and magnitude of the MCA (PAGES 2k Consortium~~, 2013). To further improve our understanding of past climate changes~~), this issue has not yet been adequately settled. Hence, there is still a great need to produce and improve empirical proxy data~~.~~ to further our understanding of near and distant climate changes.

Tree-rings are widely recognized as an excellent ~~proxies of~~proxy of past climate due to their sensitivity to growing-season ~~temperatures due to~~conditions, and their annual resolution ~~and~~with absolute dating (Briffa et al., 2001). The high~~-~~-latitude region of Fennoscandia in ~~northwestern~~northwest Europe ~~has a strong tradition in~~is well-suited to dendrochronological research, ~~and its~~with large tracts of relatively~~-~~-accessible boreal forests ~~with~~and some of the world's most temperature~~-~~-sensitive conifers (St. George, 2014) ~~and~~ in combination with favourable ~~preserving~~ preservation-conditions ~~of dead wood (see below),~~for deadwood. These make the region well~~-~~-suited for ~~development of~~developing long tree-ring chronologies, extending back over the past millennia (Linderholm et al., 2010). In addition to the multi-millennial tree-ring width chronologies from Torneträsk (Grudd et al., 2002), Finnish Lapland (Helama et al., 2002, 2008) and Jämtland (Gunnarson et al., 2003), several millennium-long tree-ring datasets were produced within the EU funded "Millennium" project (McCarroll et al., 2013). ~~Due~~We stress that, compared to ~~the superior performances of~~ ring width, maximum latewood density (MXD~~, e.g. Briffa et al., 2002), and~~) or the recently developed ΔDensity method (Björklund et al., 2014a; 2015), ~~as~~ are preferred warm-season temperature ~~indicators, it has been shown that these~~ proxies~~ are to be preferred when high-resolution reconstructions of Late-Holocene temperatures are targeted.~~. In Fennoscandia, most of the sampling for millennium-long temperature reconstructions ~~have been~~has focused ~~to~~on regions close to the latitudinal tree limit (Esper et al. 2012; McCarroll et al. 2013; Melvin et al. 2013). However, to better represent the whole of Fennoscandia~~ with more fidelity~~, data from more southerly locations are also needed (Linderholm et al., 2015). Indeed, a few studies have produced long reconstructions from more southerly sites. Helama et al. (2014) reconstructed May-September temperature variability in southern Finland (around 61 °N) for the last millennium using MXD data. In Sweden, MXD from Jämtland (63 °N; Gunnarson et al., 2011; henceforth G11, referring to the temperature reconstruction), minimum blue intensity from Mora (61 °N; Graham et al. 2011) and adjusted Δblue intensity from Jämtland and Arjeplog (63 °N and 65 °N; Björklund et al., 2015) have been used to infer past warm-season temperatures, but these reconstructions ~~only cover the last 800-900 years. Previously, Linderholm and Gunnarson (2005) used tree-ring width data to reconstruct June-August mean temperature for the last 3600 years in central Scandinavia. However, the tree-ring width data could only explain 39% of the observed temperature variance during 1861-1946, and the data had a gap between 887 CE and 907 CE.~~cover only the last 800-900 years.

The primary aim of this study ~~was~~is to extend G11 back in time to cover the MCA. ~~Moreover,~~ G11 ~~contained~~contains a mix of data: tree-line samples collected in 2006, as well as samples from historical buildings in west-central Sweden, ~~which were sampled~~collected in the late 1980s as a part of an archaeological survey by Kvartärbiologiska Laboratoriet in Lund, Sweden. The historical samples~~, covering~~ cover the period ~~between~~ 1107~~ CE and~~ -1827 CE ~~with a~~ (gap during 1292-1315 CE, were combined with), and the tree-line samples from living trees and snags (remains of dead trees) collected in the mountains incover the early 2000s, yielding a reconstruction spanning 1107period 1292–2006 CE. The geographical origins of some of the historical samples in G11 are unclear, but they likely camecome from lowland locations, about 300 meters below the present tree-line, and shouldare thus not be sub-optimal as the backbone of afor temperature reconstruction (Fritts, 1976). Therefore, we also aimed at, as far as possible, replacingaim to replace the historical samples with samples collected from past and present tree-line environments where the provenance of the trees wasis known. Using this new reconstruction, we re-examinedexamine the warm-season temperature evolution in central Scandinavia during the last 1150 years, and comparedcompare it to other reconstructions from northern and eastern Fennoscandia (Melvin et al., 2013; Esper et al., 2012; Helama et al., 2014). This improved dataset allows us to provide new insightinsights into temperature variability during the last millennium in central Scandinavia.

This paper is organized as follows: the tree-ring and meteorological data as well as reconstruction methods are presented in section 2; Section 3 presents and discusses the new central Scandinavian temperature reconstruction, and compares it with other millennium-long Fennoscandian temperature reconstructions; Conclusions are given in Section 4.

2. Data and method

2. Data and methods

2.1 Study area

The study area is located in the province of Jämtland, east of the main divide of the Scandinavian Mountains in west-central Sweden. Due to the geographical setting, there is a distinct climate gradient in the region (Linderholm et al., 2003). East of the Scandinavian Mountains, climate can be described as semi-continental. However, the proximity to the Norwegian Sea, lack of high mountains in the west, and the eastwesteast–west oriented valleys allow moist air to be advected from the ocean, providing an oceanic influence to the area (Johannessen, 1970; Johansson and Chen, 2003; Bojariu and Giorgi, 2005). Consequently, the study area is a border zone between oceanic and continental climates (Wallén, 1970). On short timescales, the climate of this area is influenced by the North Atlantic Oscillation (NAO) (; Chen et al., 1999; Busuioc et al., 2001; Folland et al., 2009), while it is affected by North Atlantic sea-surface temperature (SST) on longer timescales (Rodwell et al., 1999; Rodwell and Folland, 2002). The elevation of thisthe area ranges from 800 to 1000 m a.s.l., and scattered alpine massifs to the south reach approximately 1700 m a.s.l.. Glacial deposits dominate the area, mainly till but also glaciofluvial deposits, peatlands and small areas of lacustrine sediments (Lundqvist, 1969). *Pinus sylvestris* L. (Scots pine), *Picea abies* (L.) H. Karst. (Norway spruce) and *Betula pubescens*, Ehrh. (Mountain birch) are the main tree species in central Scandinavian Mountains. Although large-scale forestry operations have been carried out in some parts of the region, the human impacts on trees growing close to the tree line is limited (Gunnarson et al., 2012). Due to the short and cool summers, snags can be preserved for more than 1000 years on the ground (Linderholm et al., 2014) and the subfossil wood can be preserved for hundreds to thousands of years in the sediments of small mountain lakes (Gunnarson, 2008).

2.2 Description of the tree-ring data

The reconstruction consists of Scots pine tree-ring samples, collected from seven forest sites in the central Scandinavian Mountains and fromone historical buildingsbuilding in east of the mountains, were used in the new temperature reconstruction. Fig. 1 shows the locations of the sampling sites. All the sites except for the historical-building samples are located within 20km of each other, covering an altitudinal ~~gradient~~extent of 200m, with slightly different moisture-environments ranging from relatively well-~~-~~drained soils to wetter lake-shore conditions. ~~The historical building~~Ninety-nine samples ~~used in this study were collected~~ from ~~buildings in the southeast of Jämtland. Altogether, 99 samples from both~~ living and dead trees ~~and snags~~ were collected from Mount Furuberget at an elevation of ca. 650 m a.s.l~~.. The sampling sites were characterized by open pine forests~~. from a forest with limited ~~competitions between~~stand-competition. Thirty-five of the ~~trees.~~99 samples were previously used in G11. The ~~sampling sites had~~site has a thick vegetation ~~layers~~layer with woody dwarf shrubs and mosses. ~~Out of the 99 samples, 35 were previously used in the G11 reconstruction. An additional 40~~Forty samples, mainly from snags, were collected ~~from the nearby~~at Mount Håckervalen, ~~on~~ elevations ranging from 650 m a.s.l. (the present-day tree line in the area) up to 800 m a.s.l. (Linderholm et al., 2014). ~~32~~Thirty-two samples from subfossil wood were collected ~~from~~at the ~~small~~ mountain lakes of ~~Lill~~Lilla-Rörtjärnen, Östra Helgtjärnen and Jens-Perstjärnen, at 560, 646 and 700 m a.s.l~~.~~., respectively (Gunnarson, 2008~~), were also included.~~). The historical samples from Bodsjö, which made up the older part of G11, ~~was~~were downloaded from the International Tree-Ring Data Bank (ITRDB). The MXD ~~values of~~data for the historical samples ~~have been previously~~were obtained using DENDRO2003 X-ray instrumentation from Walesch Electronic (www.walesch.ch). Table 1 provides a full description of the sampling sites and the tree-ring data.

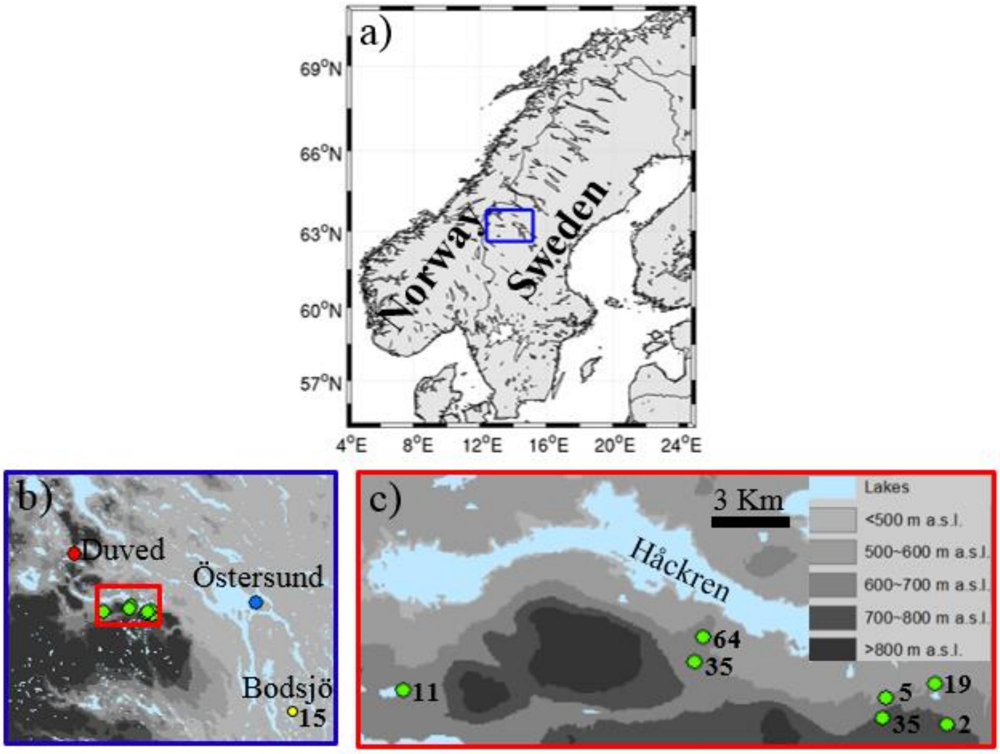

Figure 1. *Map showing the locations of (a) the study area and (b) the sites of the mountain Scots pines (green dots), historical ~~buildnings~~buildning (yellow dot) samples used in this study, and the meteorological stations Duved (~~the~~ red dot) and Östersund (~~the~~ blue dot). (c) shows the topography of the mountain Scots pines. Numbers in (b) and (c) indicate the number of samples collected from each site.*

The new MXD samples were measured at the tree-ring laboratory of Stockholm University using the ITRAX wood scanner from Cox Analytical Systems (http://www.coxsys.se). Thin laths (1.20 mm thick) were cut from each sample using a twin-bladed circular saw, and subsequently put in a Soxhlet apparatus with pure alcohol to remove resins and other compounds. After being processed in the Soxhlet for at least 24 hours, the laths were acclimatized in a room with controlled temperature (20 ℃) and humidity ~~to have~~(50%) that yielded ca. 12% ~~water~~moisture content in the wood, and then mounted in a sample holder. The samples were exposed to a narrow, high energy, X-ray beam. The chrome tube in the ITRAX was tuned to 30kV and 50mA, with 75ms step~~-~~-time. The opening time of the sensor slit was set to 20µm at each step. From the sensor, a 16-bit, greyscale, digital image with a resolution of 1270 dpi was produced. The grey levels of the image were calibrated to values of wood density using a cellulose acetate calibration wedge provided by Walesch Electronics. The MXD data was obtained using the image processing software WinDENDRO.

Zhang et al. (2015) found that MXD data~~ from the study area~~ covering the same time period but originating from different elevations/sites can have systematic differences in terms of mean values. ~~Because the~~The older snag samples in this study were found at progressively higher elevations, as well as contrasting growth environments~~, serious biases could thus be introduced into an average chronology based on all data, both in terms of the annual to decadal variability, but perhaps even more so in the longer-term trends, if~~. If the differences in ~~absolute ~~MXD values caused by elevation and local moisture conditions ~~are~~were not accounted for~~ (Zhang et al., 2015).~~, it could seriously bias the average chronology, both in terms of the annual to decadal variability and longer-term trends. Therefore, we adjusted the mean MXD values from trees growing at different elevations as well as the subfossil samples~~,~~ (representing a wetter growth environment than the tree-line trees~~,~~) to have the same mean during a common period. Following the protocol proposed by Zhang et al. (2015), we used the mean MXD values of the samples from Furuberget-north for the period 1300-1550 CE as the reference to correct the in-situ data (see Table 1 for adjustment values for each site). The Furuberget-north data was chosen as reference because it had the highest sample replication and widest temporal coverage. The samples from Furuberget-south and Håckervalen-north were not adjusted, because both sample groups were collected from sites where growing conditions (open forests on relatively well-drained soils) and elevations were similar to the reference samples. The mean MXD values of the corrected in-situ data and the data from Furuberget-north for the period 1107-1291 were subsequently used as the reference to correct the historical-building data from Bodsjö.

~~In a tree-ring MXD series, MXD values change with age. Therefore, when applying the mean-adjustment methodology (Zhang et al., 2015) this should be taken into consideration, and each group of samples should have a homogeneous age distribution in the selected reference period, as well as the adjustment periods. The time-spans of the adjusted and reference samples are shown in Fig. A.1. To further validate the mean-adjustment of this data material,~~The time-spans of the adjusted and reference samples are shown in Fig. A.1. Some of the samples do not fully cover the common periods, so only the part of a sample overlapping with the common periods was used to compare with reference mean values when calculating the adjusted value for each sub-site. In the previous study (Zhang et al., 2015) we found that the differences in mean absolute MXD values among the sites of different elevations in a given period were larger than among the sites of similar elevation between MCA and LIA. Therefore, we argue that the slight-mismatch of the time-spans within the common periods among the sub-sites should not bias the mean-adjustment. Fig. A.2 shows the age-aligned average curves for the samples partly or fully covering the reference periods before and after the mean-adjustment, along with the average curve of the reference samples. The average curves were smoothed using spline functions. The smoothed average curves show that MXD values generally decrease with ~~tree's~~tree age. The average curve of the adjusted samples displays the same mean MXD level as the average curve of the reference samples. ~~This result indicates that the distribution of ages is not the main reason why the mean values of the samples in different groups/sites are different in the reference~~

period. The samples from Furuberget-south and Håckervalen-north were not adjusted, because both groups of samples were collected from sites where growing conditions (open forests on relatively well drained soils) and elevations were similar to the reference samples.

In a tree-ring MXD series, MXD values change with age. Therefore, this should be taken into consideration when applying the mean-adjustment methodology (Zhang et al. 2015), and each group of samples should have a homogeneous age distribution in the selected reference period, as well as the adjustment periods. Mean age statistics of the reference and mean-adjusted samples are shown in Table. A.1. During the common period 1300-1550, the mean age of samples at the reference site (Furuberget-north) is 105 years, Håckervalen-south: 101 years, Ö Helgtjärnen: 90 years, Lilla-Rörtjärnen: 86 years, Jens Perstjärnen: 153 years. During the common period 1107-1291, the reference-site-mean-age is 70 years and for Bodsjö: 79 years. This shows that the mean ages of most of the sites at these common periods do not deviate substantially from each other (the mean ages represent mature trees, but juvenile or old-age trees which can be said to deviate in mean values just because of age). From Fig. A.2a, we can see that the difference of the MXD values at this age range is much smaller than the difference caused by the elevation/local-environment (see also the adjusted values in Table 1). Therefore, we argue that mean-adjustment should not be biased by tree age in these sample materials.

Table 1. *Summary of the tree-ring MXD data.*

Sampling sitessite	Elev	TS	NS	MSL	AMXD	MS	AC1	M-adj (g/cm^3)
Furuberget-north	650	837-1112	3	156	0.74	0.118	0.566	0
		1189-2005	61	197	0.69	0.124	0.599	0
Furuberget-south samples from the G11 study	650	1497-2008	35	193	0.64	0.133	0.457	0
Håckervalen-south	750	783-1265	30	130	0.66	0.125	0.415	0.112
		1276-1520	5	128	0.67	0.109	0.532	0.112
Håckervalen-north	650	1778-2011	5	213	0.71	0.165	0.314	0
Lilla-Rörtjärnen*	560	952-1182	13	90	0.67	0.122	0.572	0.085
		1290-1686	5	198	0.66	0.111	0.676	0.085
		1750-1861	1	112	-	-	-	0.085
Ö Helgtjärnen*	646	929-1093	6	121	0.62	0.124	0.715	-0.079
		1119-1333	3	104	0.72	0.122	0.625	-0.079
		1446-1568	2	110	0.76	0.106	0.676	-0.079
Jens Perstjärnen*	700	1196-1382	2	153	0.62	0.133	0.753	0.058
Bodsjö (historical buildings in Jämtland, Sweden) samples from the G11 study	377	1107-1291	15	158	0.84	0.082	0.676	-0.112

Elev: sampling elevation (m a.s.l); TS: time span (years CE); NS: number of samples; MSL: mean segment length (year); AMXD: average MXD (g/cm^3); MS: mean sensitivity; AC1: first-order autocorrelation; M-adj: the adjusted values that added to each sample of the corresponding site; * indicates data from subfossil wood collected from lakes. Some of the 'mean tree ages' ~~were~~are less than 100 years, because the MXD measurement ~~was~~is only a part of a tree-ring width series, which ~~was~~is much longer. The temporal restriction of these samples ~~was~~is due to some parts of the samples being too rotten for MXD to be measured. MXD data from Furuberget-north, Håckervalen-south, Håckervalen-north, Lilla-Rörtjärnen, Östra Helgtjärnen and Jens Perstjärnen was not included in G11. MXD data from the historical ~~buildings~~building was downloaded from the International Tree-Ring Data Bank (ITRDB), and was previously used in G11.

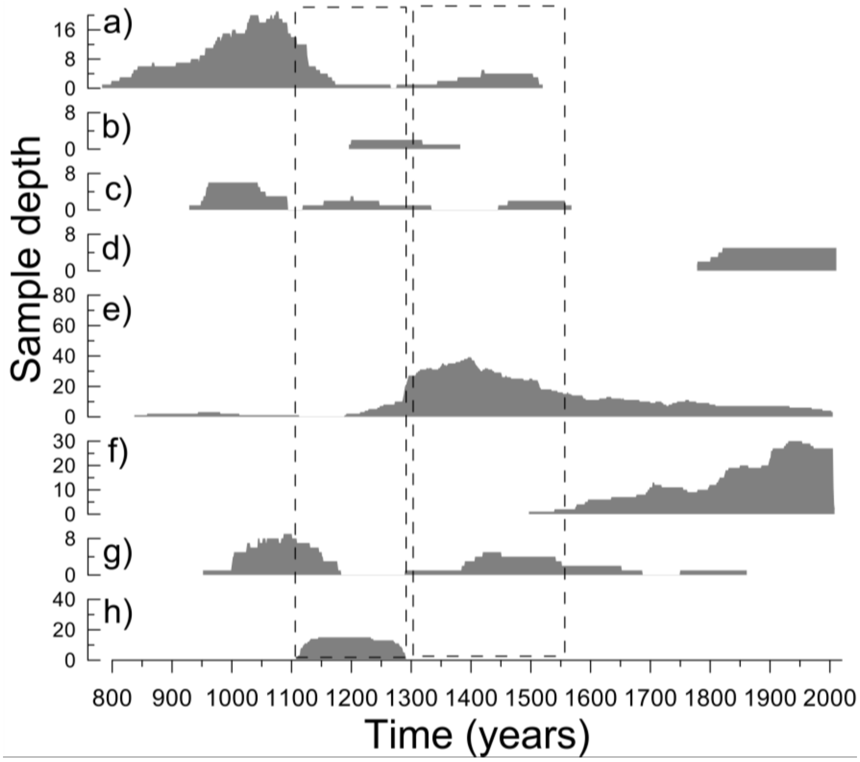

Figure 2. *Sample replication through time at (a) Håckervalen-south, (b) Jens Perstjärnen, (c) Ö Helgtjärnen, (d) Håckervalen-north, (e) Furuberget-north, (f) Furuberget-south (G11), (g) Lilla-Rörtjärnen and (h) Bodsjö. The dashed lines mark the two reference periods for mean-adjustment (see main text).*

2.3 Standardisation methods

~~If tree-ring data is going to be used to attain~~To obtain high-quality climate information from tree-ring data, it is necessary to remove as much non-climatic "noise" as possible before building a chronology from the individual tree-ring series (Fritts, 1976). The non-climatological growth ~~expression is usually represented with a least square fitted negative exponential function, polynomial or spline~~effect is usually represented with a least-squares-fitted negative exponential function, polynomial or spline (Fritts, 1976; Cook and Peters, 1981). This is subsequently removed from corresponding values of the measurements, either by subtraction or division, in a process termed standardisation. This approach is widely used, but it severely limits the preservation of low-frequency variability in long chronologies (based on several generations of trees), because the mean values of all the tree-ring series are adjusted to the same level after standardisation. This limitation in preserving low-frequency variability is referred to as the "segment length curse" (Cook et al., 1995; Briffa et al., 1996).

~~This~~The limitation can be overcome by quantifying the non-climatological growth expression for an entire population as an average of the growth of all samples aligned by cambial age, which then can be represented by a single mathematical function. Subsequently this function is removed from each individual tree-ring measurement, an approach called Regional Curve Standardisation (RCS; Briffa et al., 1992). ~~However, by~~By using one single function for all tree-ring series, less unwanted mid-frequency variability ~~may be~~is removed in the attempt to preserve the low-frequency (>segment length) variability (Melvin, 2004), along with possible trend distortion as described in ~~(~~Melvin and Briffa~~,~~ (2008~~; Melvin and Briffa, 2014a, 2014b).~~). Melvin and Briffa (2014a, 2014b) showed that ~~using~~ multi-curve RCS ~~can~~could, however, efficiently remove these biases. Alternatively, ~~the~~ non-climatological ~~expression~~effects in tree-ring data can be quantified with an individual signal-free (SF) approach, described in Melvin and Briffa (2008), but this approach is also limited in the lower-most frequencies (Björklund et al., 2013).

However,~~ by~~ using the SF individual fitting approach and at the same time letting the derived functions ~~to~~ have a similar mean as ~~their~~the respective cambial age segment of the regional curve (RC) before subtraction into indices, stand competition etc. can also be addressed without losing the long timescale component (Björklund et al., 2013). This method is a hybrid of the RCS and individual SF standardization, and was termed RSFi. In this study, we produced MXD chronologies using two standardisation methods: two-curve signal-free RCS (fitted by age-dependent splines) and RSFi (fitted by age-dependent splines), where the RSFi chronology was used for the new reconstruction. In both methods, residuals between raw data and fitted functions were calculated, and subsequently averaged to produce the final chronology. The standardisations were performed using the software RCSsigFree (Cook et al., 2014) and CRUST (Melvin and Briffa, 2014a, 2014b). The expressed population signal (EPS) criterion was used to evaluate the robustness of the chronology. An EPS value represents the percentage of the variance in the hypothetical population signal in the region that is accounted for by the chronology, where EPS values greater than 0.85 are generally regarded as sufficient (Wigley et al., 1984). Here the EPS values were calculated in a 50-year window with a 1-year lag.

2.4 Instrumental data

Monthly temperature data from the closest meteorological station, Duved (400 m a.s.l., 63.38 °N, 12.93 °E), was used to assess the temperature signal reflected by the chronology. Since the data from this station only cover the period 1911-1979, the data was extended back to 1890 CE and up to 2011 CE using linear regression on monthly temperature data from an adjacent station: Östersund (376 m a.s.l., 63.20 °N, 14.49 °E). Data from Östersund explained on average 91.5% of the ~~interannual~~inter-annual variance of Duved monthly ~~temperature~~temperatures (based on the overlapping period 1911-1979). The temperature data from Östersund came from two sources: the Nordklim dataset (1890-2001) (Tuomenvirta et al., 2001~~),~~) and Swedish Meteorological and Hydrological Institute (SMHI, 2001-2011 CE). The locations of Duved and Östersund stations are shown in Fig. 1.

2.5 Climate signal and reconstruction technique

We calculated correlations between the new MXD chronology and instrumental monthly mean temperatures from Duved over the period 1890-2011 CE. Fig. 3 shows that ~~it is~~these are significantly correlated ($p < 0.01$) ~~with~~for all individual months from April to September, and the correlation with mean April-September temperature is 0.77~~ (~~. The correlation is 0.81 ($p<0.01$) if only ~~interannual~~inter-annual variability were considered~~)~~. Same results were obtained (0.77, $p<0.01$) when correlating the MXD chronology with mean April-September temperature from the closest grid in the CRU TS3.23 0.5°×0.5° dataset (Harris et al., 2014) over the period 1901-2011. A transfer model was developed using simple linear regression, where the April-September temperature anomalies (deviations from the 1961–1990 mean) were set as the predictand and the MXD data of the current year (*t*), as the predictor. The temporal stability of the model was tested with a split sample calibration/verification procedure (Gordon, 1982), where the period of MXD and meteorological data overlap (1890–2011) was divided into two periods of roughly equal length (1890-1950 CE and 1951-2011 CE, respectively). Calibration and verification statistics were then calculated for the first and second half of the period, respectively. The calibration and verification periods were then exchanged and the process repeated. The validation was performed using the explained variance (R^2), Reduction of Error (RE), Coefficient of Efficiency (CE) statistics (National Research Council, 2006).

The final model was calibrated over the full 1890–2011 period. The uncertainty of the reconstruction was estimated from two sources: chronology characteristics (temporal variations in replication) and the calibration statistics according to the methods of Yang et al. (2014). The uncertainty in the chronology was estimated by +/- 2 times the standard error (i.e. the standard deviation of all MXD index values in each year divided by the square root of the sample replication). The calibration uncertainty was estimated from the standard deviation of the reconstruction residuals (i.e. the difference between observed and reconstructed temperatures). The error of the reconstruction was estimated by the square root of the sum of the squared chronology error and the squared calibration uncertainty. The uncertainty of the reconstruction was then estimated by +/- 2 times of the reconstruction error.

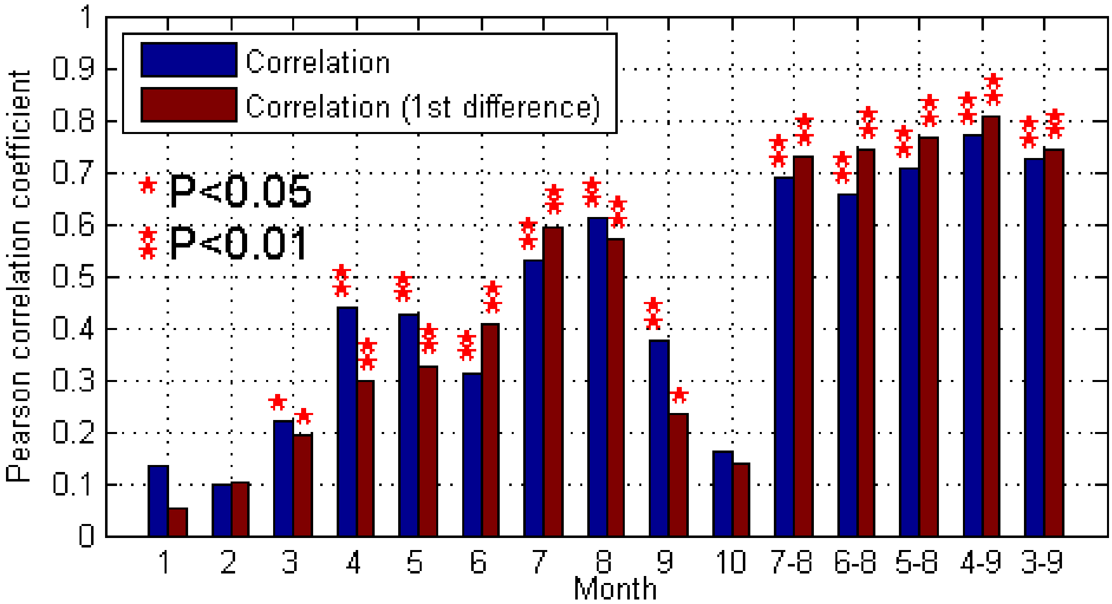

***Figure 3**. The correlations between the mean-adjusted MXD chronology, standardised with the RSFi method, and observed monthly mean temperatures from Duved meteorological station over the period 1890-2011. The correlations are given from January to October of the present year and July-August, June-August, May-August, April-September (warm season) and March-September means.*

3. Result and discussion

3.1 The new reconstruction and reconstruction statistics

The calibration and verification statistics are summarized in Table 2. The RE and CE statistics are well above zero, and thus pass the validation tests (National Research Council, 2006). Fig. 4a shows a linear relationship between the MXD data and Duved April-September mean temperatures over the period 1890-2011. The reconstructed and observed warm-season temperatures show good agreement on ~~interannual~~inter-annual and ~~multidecadal~~multi-decadal timescales (Fig. 4b). The reconstruction has a slightly~~-~~ smaller spatial representation than observed station data when compared to gridded temperatures (Fig. 5). However, the new reconstruction still represents much of central Fennoscandia, and has a much more southerly expression than the northern MXD chronologies mentioned in the introduction (Melvin et al., 2013; Esper et al., 2012; McCarroll et al., 2013), and more western expression than Helama et al., (2014).

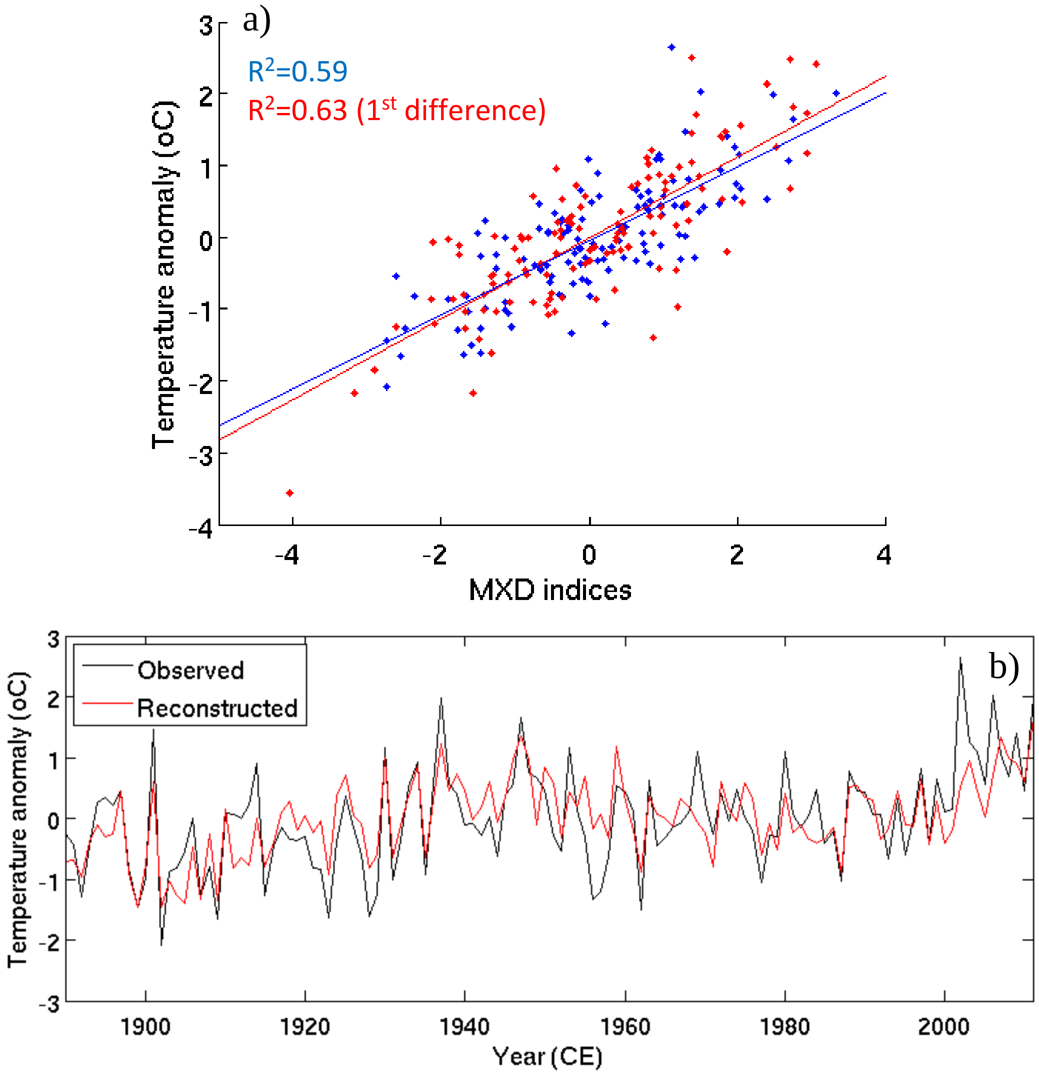

Figure 4. *(a) Scatter plot of the MXD indices versus observed warm-season temperature anomalies (relative to 1961-1990 mean) from Duved (blue), and their respective 1st difference components (red), and (b) a comparison of reconstructed warm-season ~~temperature~~temperatures (red) and observed Duved warm-season ~~temperature~~temperatures (black) over the period 1890-2011.*

Table 2*. The calibration and verification statistics of the warm-season temperature reconstruction.*

	MXD RSFi chronology		
Calibration period	1890-1950	1951-2011	1890-2011
Correlation coefficient, R	0.82***	0.68***	0.77***
Explained variance, R^2	0.67	0.47	0.59
No. of observations	61	61	122
Verification period	1951-2011	1890-1950	-

Explained variance, R^2	0.47	0.67	-
~~RE~~Reduction of error (RE)	0.56	0.72	-
~~CE~~Coefficient of efficiency(CE)	0.45	0.66	-
Slope	-	-	0.~~570~~~~3~~57
Intercept	-	-	-0.~~1453~~145

Notes: *** = correlation is significant at the p<0.01 level~~; RE = reduction of error; CE = coefficient of efficiency.~~.

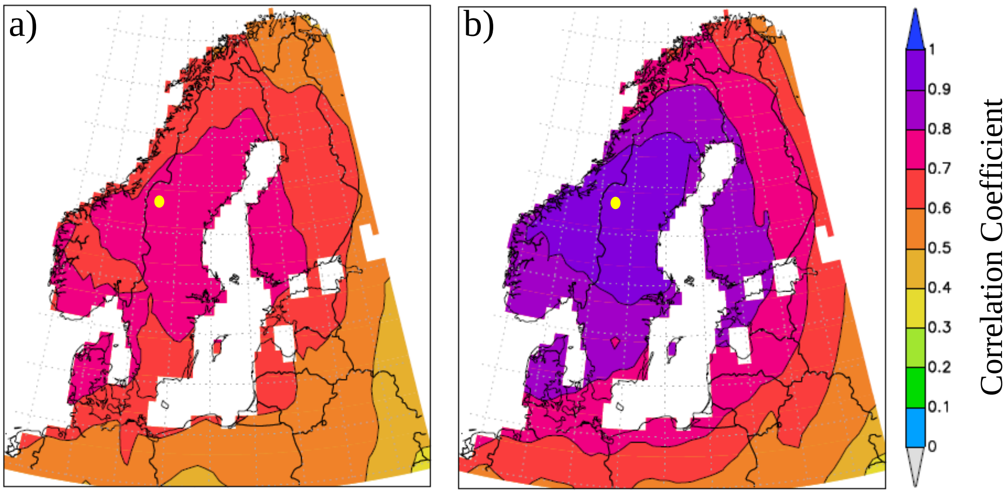

Figure 5. *Field correlations between gridded warm-season temperature from the CRU TS3.23 0.5 °×0.5 °dataset (Harris et al., 2014) during the period 1901-2011 CE and (a) reconstructed warm-season ~~temperature~~temperatures (this study), and (b) observed Duved warm-season ~~temperature~~temperatures. The yellow dots mark the approximate locations of the sampling sites. The field correlation maps were made using the 'KNMI climate explorer' (Royal Netherlands Meteorological Institute; http://climexp.knmi.nl; van Oldenborgh et al., 2009).*

3.2 Central Scandinavian warm-season temperature evolution

Fig. 6a shows that the differences between the mean-adjusted and the non-adjusted MXD chronologies mainly occur before 1300 CE. The mean-adjusted chronology shows lower values between 1150 and 1300 and higher values between 850 and 1100, compared to the non-adjusted chronology. Clearly, not using the mean adjustment would have large impacts on the interpretation of the temperature evolution during the last millennium. If possible, this principle should always be utilized when data from slightly different growth environments, with sufficient overlap, are composited~~,~~ before ~~standardization~~standardisation. Fig. 6c shows that the EPS values are above 0.85 during most of the last millennium, testifying to the robustness of the chronology in representing the hypothetical population signal. However, there is a dip in EPS values during the period 1150-1200 which reduces the validity of the reconstruction in this period. EPS values are influenced by two factors: number of samples and inter-series correlations (Wigley et al., 1984). Obviously, the dip in EPS values in this case should be attributed to relatively weak inter-series correlation over that time period compared to other time periods during the last millennium. It should be noted that the chronology during this period consist of both tree-line and low-elevation (historical) samples. However, during most of the last millennium, the variability of the tree-ring samples from the two sources (tree-line and historical) ~~does~~do not show obvious differences at ~~interannual~~inter-annual (not show) to centennial (Fig. 7) timescales.~~ Therefore, to find out the reason for the low inter-series correlation more in situ samples from that period are needed.~~

When comparing the MXD chronologies based on the RSFi and the two-curve signal-free RCS standardisation (Fig. 6b), the two chronologies are ~~rather~~very similar at multi-decadal timescale. Because of this, and the assumption that the former methodology has a greater chance at removing mid-frequency noise (Björklund 2014b), we chose the RSFi method for our reconstruction. Fig. 6d shows the reconstructed warm-season ~~temperature~~temperatures in central Scandinavia, henceforth referred to as C-Scan, during the past 1150 years. C-Scan displays a cooling trend over the period 850-1900, followed by a sharp temperature increase in the 20th century. C-Scan suggests a moderate MCA warm-peak during ca. 1000 CE to 1100 CE in central Scandinavia. ~~Improved understanding of spatiotemporal characteristics of MCA is important in terms of understanding the dynamic origin of MCA. Proxy-based spatial annual temperature reconstructions have delineated a strong and persistent LaNiña-like climate pattern globally during MCA. The spatial pattern of the reconstructed temperature changes (MCA-LIA) imply that MCA may be caused by dynamical responses to natural radiative forcing (Mann et al., 2009). However, climate model simulations (as shown in González-Rouco et al., 2011) with strong solar forcings failed to reproduce such a spatial pattern (in Mann et al., 2009). In contrast, the climate model with reduced solar forcing, allowing for internal variability to be more prominent, show less uniform temperature responses in sign as those of the reconstructed global annual temperature changes (in Mann et al., 2009). Therefore, internal variability of climate system as a possible reason of the MCA-LIA anomalies has been suggested (González-Rouco et al., 2011). Recently, Goosse et al. (2012) simulated MCA-LIA transition using data assimilation method, and indicated spatial pattern of temperature during MCA could be caused by weak radiative forcing combined with a modification of atmospheric circulations, and the changes of the atmospheric circulations could be related to either climate-system internal dynamics or dynamical responses to weak changes of radiative forcing. We can see that reconstructions of surface temperature pattern provide possibilities for all these attribution studies. Therefore, high-quality temperature reconstructions in regional and sub-regional scale are still needed.~~ Our reconstruction indicates that the warm-season warmth during MCA is not so pronounced in central Scandinavia, which ~~improves~~ adds further detail to our knowledge about the spatial pattern of surface air temperature on ~~global and~~the regional ~~timescales~~scale. The new reconstruction ~~will also add values to existing regional~~is therefore very important for future spatial temperature reconstructions ~~(e.g.~~such as Luterbacher et al., (2016)

C-Scan ~~also~~ indicates that, in this region, the cold period known as the Little Ice Age (LIA, Grove, 2001) ~~spanned~~spans the mid-16th century to the end of the 19th century, where the coldest 100-year period ~~was~~is found in the late 18th to late 19th century. Both the coldest 10- and 30-year periods ~~were~~are found around 1600 CE. The warmest 10~~-~~, 30- and 100-year periods during the last millennium ~~were~~are all found in the 20th century. Comparing the MCA to the 20th century, the warmest 10~~- and~~-, 30- and 100-year in the 20th century are 0.3 ℃, 0.1 ℃ and 0.03 ℃ warmer in the 20th century than those in the 10th and 13th centuries respectively. However, the reconstruction based on the two-curve signal-free RCS standardised chronology indicates that the coldest 100-year period appears in 18th century during the last millennium.

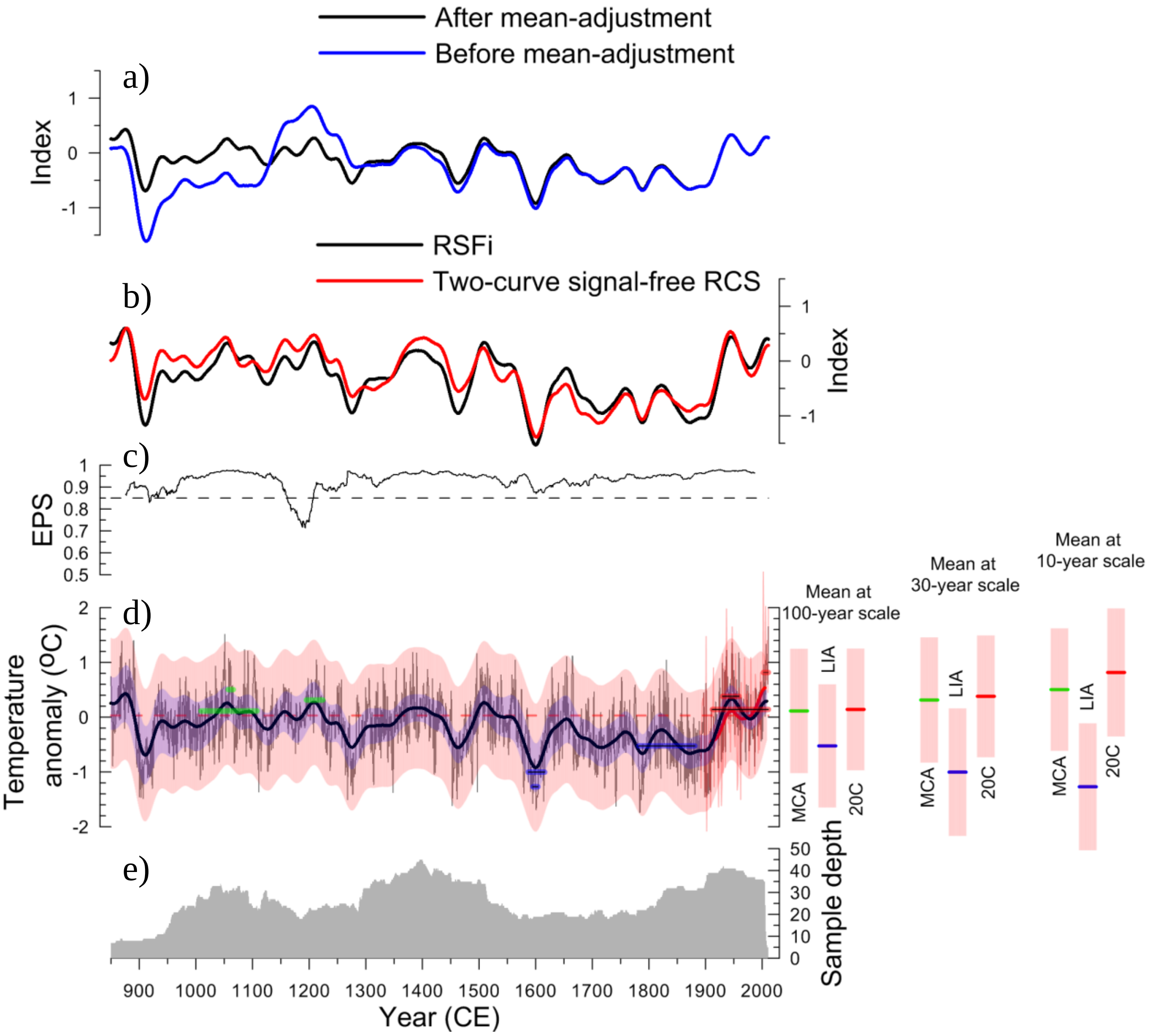

***Figure 6**. Characteristics of the central Scandinavian MXD chronology and the resulting warm-season temperature reconstruction: (a) The MXD chronologies based on samples without mean-adjustment (blue) and after mean-adjustment (black). (b) Comparison of the ~~multidecadal~~multi-decadal (after 51-year Gaussian filtering) variability of the MXD chronologies standardised by the two-curve signal-free RCS standardisation method (smoothed by age-dependent spline, the red curve) and the RSFi standardisation method (fitted by age-dependent spline, the black curve). (c) Expressed Population Signal (EPS) through time of the chronology. The dashed line shows the 0.85 threshold. (d) Reconstructed annual (grey) and 51-year Gaussian filtered (bold black) warm-season temperature variability in central Scandinavia over the period 850-2011. Also indicated is the chronology uncertainty (purple shading) and the total uncertainty of the reconstruction (pink shading. This includes chronology uncertainty and reconstruction uncertainty) expressed as +/- 2 times the standard error. Observed warm-season temperatures are shown by the thin red (annual) and the bold red (after 51-year Gaussian filtering) curves, with the red dashed line indicating the 1961-1990 mean. The short lines to the right of panel (d) mark the mean temperature levels of the warmest 100, 30 and 10 years in MCA (10^{th}-13^{th} century (Grove and Switsur, 1994)) (green) and 20^{th} century (red), and the coldest 100, 30 and 10 years in the LIA (14^{th}-19^{th} century (Grove, 2001)) (blue). The time spans are marked on the corresponding positions on the temperature curve. The coloured short lines with thin solid black line in the centre mark the time spans of the warmest*

and coldest 100, 30 and 10 years during the past 1200 years. (e) The grey shading indicates the sample depth of the MXD chronology.

Fig. 7 shows a comparison between C-Scan and G11. The two reconstructions show coherent variability at ~~multidecadal~~multi-decadal to centennial timescales during the period 1300-2000. However, the 12th century is portrayed as much warmer in G11 than in C-Scan, and we largely attribute this discrepancy to the omission of adjusting the mean values of the samples from different elevations in G11. However, if this feature is disregarded, the comparison between C-Scan and G11 actually show that the historical-building samples perform quite well in representing the temperature variability at ~~multidecadal~~multi-decadal to centennial timescales. Considering the performance of the historical samples and the~~ temporarily~~ low replication of the newly collected samples around 1200 CE, we argue that it is better to use the historical samples when sample depth is low, than not to use ~~it~~them at all. Therefore, we included mean adjusted historical samples for the period 1107-1291 CE in our reconstruction. The EPS values are improved over that time period, but still do not reach the 0.85 threshold.

Compared to G11, the merit of C-Scan is manifested by three aspects: 1) C-Scan covers the whole of MCA and can be used to interpret the temperature evolution during this important phase in ~~central Scandinavia.~~our temperature history. 2) The application of the mean-adjustment method. Our results suggest that also the historical-building samples, used in G11, should be separately mean-adjusted according to their origin and mean values, and not be treated as a homogenous dataset. 3) C-Scan is~~ to~~ 92% based on the samples collected from a relatively small mountain area, close to the local tree line, compared to G11~~ that was ~~, which is 73% based ~~on 73% ~~historical samples. Even though the historical samples seemingly perform in a similar way ~~as~~to the tree-line samples, trees at the limit of their distribution should be more sensitive and thus perform better, and ~~be~~are preferred ~~in a reconstruction~~for reconstructions, according to the principle of limiting factors (Fritts, 1976). This is perhaps corroborated by the fact that the new reconstruction displays a larger variance at some periods, such as stronger cooling events around 1450 CE and 1600 CE than those in G11. This could be interpreted as a more coherent variability (lower noise level) among the newly collected samples than the historical-building samples, which is always ~~strived for~~desirable.

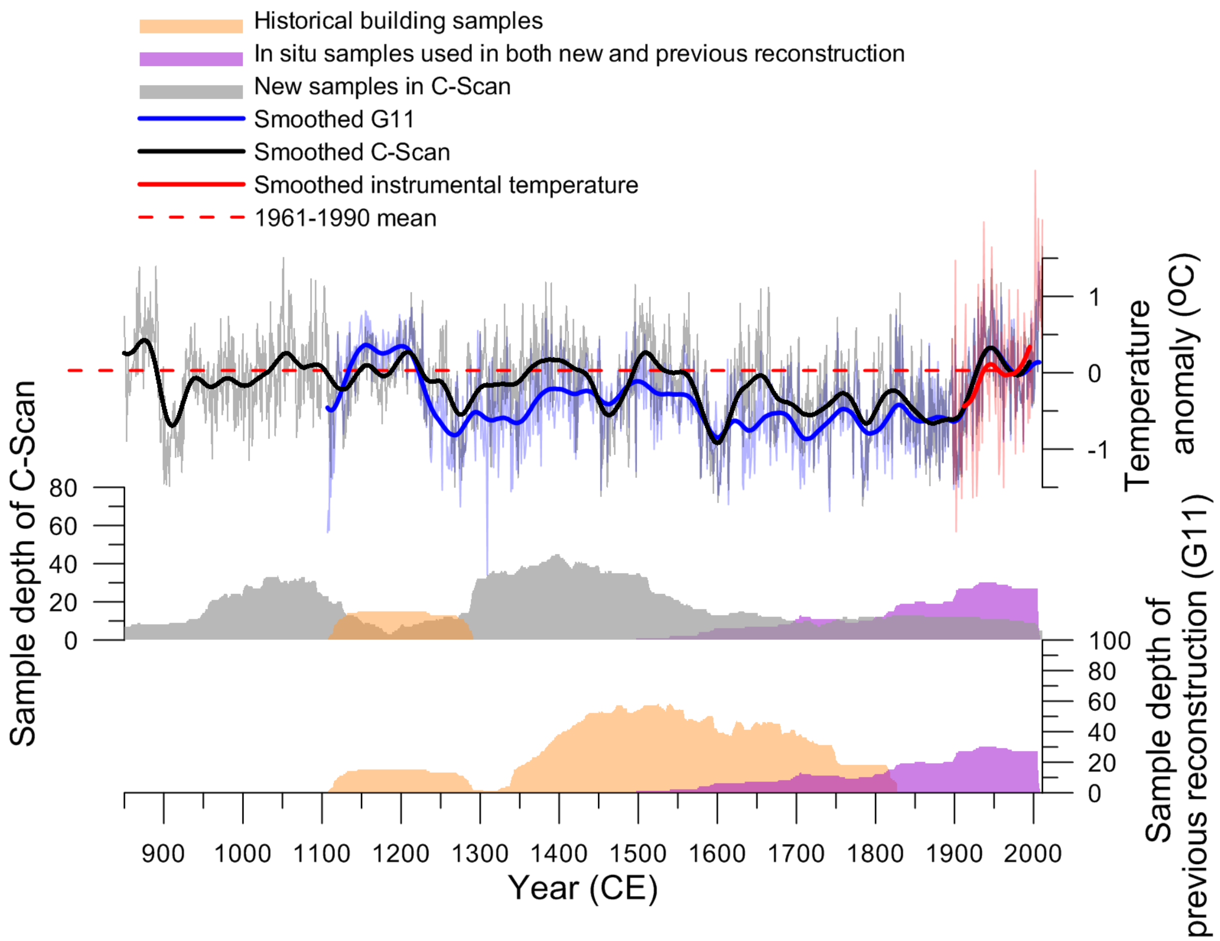

Figure 7*. A comparison between C-Scan (~~the~~ thin grey curve) and G11 (~~the~~ thin blue curve, Gunnarson et al., 2011). Bold black and blue curves show the variability after 51-year Gaussian filtering. The sample depths of different origins used in the two reconstructions are marked by the orange, black and purple (C-Scan) and orange and purple (G11) shadings, respectively. The red curves indicate the observed year-to-year temperature variability (thin line) and its 51-year Gaussian filtered variability (thick line). The dashed red curve shows the observed 1961-1990 mean warm-season temperature.*

3.3 Comparing C-Scan with other Fennoscandian summer temperature reconstructions

~~As mentioned earlier, annually~~Annually resolved summer and warm-season temperature reconstructions covering the entire last millennium, based on MXD data, have almost exclusively focused on northern Fennoscandia (McCarroll et al., 2013, henceforth referred to as Mc13; Esper et al., 2012; Melvin et al., 2013; Matskovsky and Helama, 2014, henceforth referred to as MH14), with the exception of the reconstruction for southern Finland (Helama et al. 2014, henceforth referred to as H14). A general feature of these reconstructions is a cooling trend during the ~~past~~last millennium until the end of 19th century, consistent with the reduction in high-latitude summer solar insolation related to orbital forcing (Helama et al., 2010; Esper et al., 2012), followed by an abrupt warming trend during 20th century, related to increasing CO_2 concentrations in the atmosphere (Stocker et al., 2013). However, differences among these reconstructions, even those focused on the northernmost part of the region, have been discussed~~,~~ (e.g. Matskovsky and Helama, 2014; Linderholm et al., 2015). In Fig. 8, C-Scan is compared with MH14, Mc13 and H14. C-Scan shows smaller variance than the other three reconstructions, likely because it was calibrated based on a longer time-window (i.e. April-September) than the others (MH14: June-July; Mc13: June-August; H14: May-September). The ~~multidecadal~~multi-decadal variability of H14 generally differs from the other onesothers, where the pronounced cooling during the LIA stands out. The other segments of the reconstructions agree quite well, although Mc13 in generalgenerally shows cooler anomalies than MH14 and C-Scan. The largest discrepancy among the reconstructions is found between 900 and 1100 CE (the MCA), where MH14 shows persistent warm anomalies, whereas Mc13 shows cooling and in C-Scan temperatures are only slightly above the long-term average. MCA temperatures in H14 are similar to C-Scan, but slightly higher.

June-August mean temperature variability are rather coherent with April-September mean temperature variability at different timescales in Scandinavia (not shown), so different calibration time-windows are not likely the reason why the four reconstructions show differences in their variability. It is possible that at least part of the discrepancies among the reconstructions can beis partly attributed to methodological issues, such as changes in numbers of samples through time in the chronologies, or periods where trees show less coherent growth patterns (e.g. the 1150-1200 period in C-Scan). Such issues can be alleviated through careful selection of the tree-ring data and more coherent standardisation method and parameters (Frank et al., 2010; Björklund et al., 2014b). However, the differences in reconstructed temperatures may also be expressions of sub-regional differences associated with varying atmospheric circulationscirculation patterns that influence across Fennoscandia through time. Linderholm et al. (2015) discussed the possibility that changes in the average positions of circulation patterns such as the NAO, related to changes in the polar jet stream configuration, could have an influence on the homogenous summer temperature pattern in Fennoscandia observed today. Likely, due to the proximity of the study region to the ocean, theThe influence of e.g. the Atlantic MultidecadalMulti-decadal Oscillation can also be of importance, due to the proximity of the study region to the ocean. Furthermore, Irannezhad et al. (2014) found that the trends of observed annual and seasonal surface air temperaturetemperatures show spatial differences in Finland, and that the warm-season temperaturetemperatures can be related to different regional-scale circulation patterns such as the East Atlantic, West Russia, Scandinavian and West Pacific patterns in different sub-regionregions. Thus, it is likely that summer temperature variability in different sub-regions throughout Fennoscandia areis controlled by different circulation patterns, and that asymmetric changes ofin these circulation patterns induce spatial differences in summer temperature evolution. A more detailed study of regional temperature patterns in Fennoscandia, and their associated regional-scale circulation patterns, in Fennoscandia canwould be useful to test if the spatial differences of warm-season temperature evolution occur in the past during different climate settings, especially during the MCA, being partly an important analogue to the present-day warming.

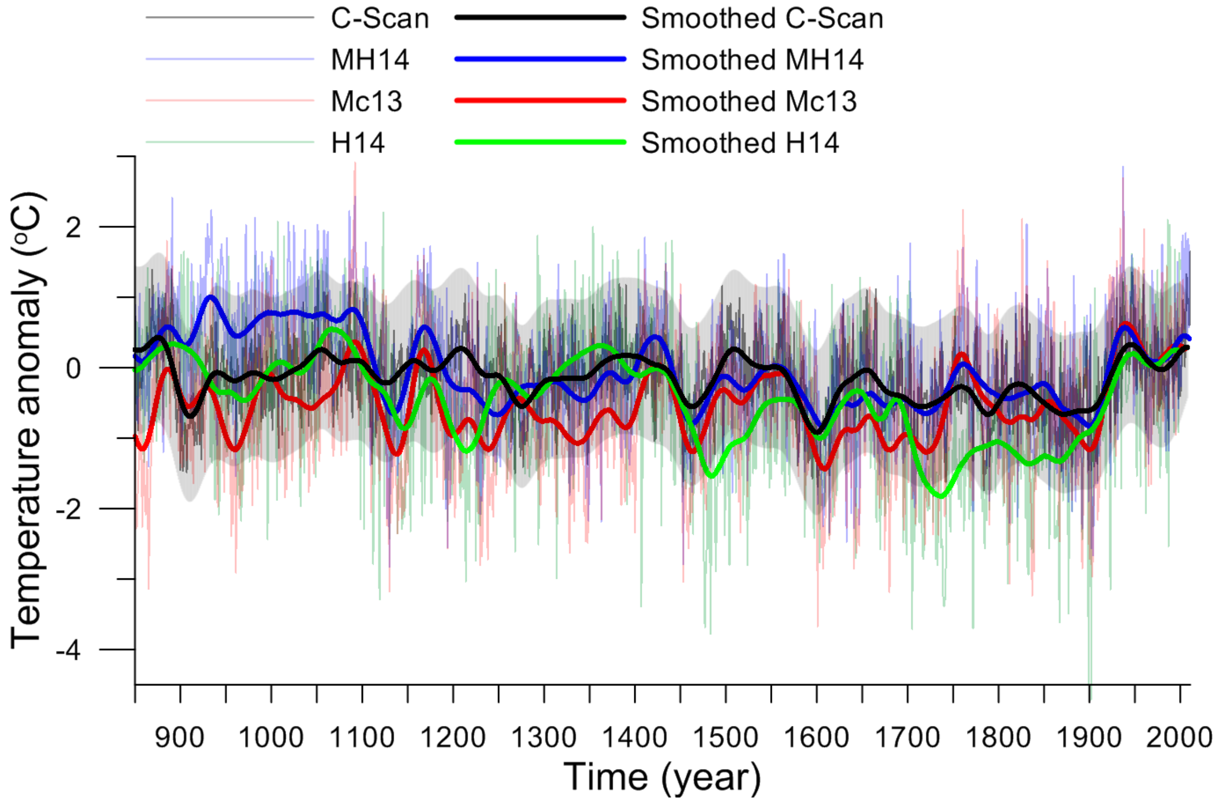

Figure 8. *Comparison of temperature anomalies (from 1961-1990 period) inferred by four temperature reconstructions covering the whole last millennium: C-Scan (April-September, this study, black), MH14 (June-July, MXD, blue, Matskovsky and Helama, 2014), Mc13 (June-August, multi-proxy, red, McCarroll et al., 2013) and H14 (May-September, MXD, green, Helama et al., 2014). Bold curves show the variability after 51-year Gaussian filtering. The black shading indicates the total uncertainty of C-Scan (including chronology uncertainty and reconstruction calibration uncertainty), as expressed as +/- 2 times the standard error.*

4. Conclusions

In this study we ~~successfully~~ updated and extended the MXD data that was previously used to reconstruct central Scandinavian warm-season temperatures. The new reconstruction, C-Scan, now extends back to 850 CE ~~including also~~, and includes the MCA. Compared to the previous reconstruction, G11, ~~in C-Scan~~ the issue of biases arising from samples from different locations was appropriately addressed and corrected using the mean-adjustment method~~, and~~. C-Scan is largely based on high-quality tree-line samples collected from a smaller area.

C-Scan suggests a moderate MCA warm-peak during ca. 1000 CE to 1100 CE in central Scandinavia and a LIA lasting from the mid-16th century to the end of the 19th century. During the last millennium, the ~~late 18th century to late 19th century was the coldest 100-year period in central Scandinavia, where the~~ coldest 10- and 30-year periods occurred around 1600 CE~~.~~ in central Scandinavia. The warmest 10~~, 30~~- and ~~100~~30-year periods were found in 20th century. C-Scan indicates lower ~~temperature~~temperatures during the late MCA (ca. 1130-1210 CE) and higher ~~temperature~~temperatures during the LIA (1610-1850 CE) than G11.

Some differences in ~~multidecadal~~multi-decadal to ~~multicentennial~~multi-centennial variability between C-Scan and other MXD-based temperature reconstructions from Fennoscandia were found, suggesting regional differences of summer/warm-season temperature evolution, possibly linked to varying influences of atmospheric circulation patterns. However, this needs to be further investigated.

~~Supplementary~~

Appendix A

The new reconstruction, C-Scan, will be uploaded to NOAA and BALPAL, and all the data published in this study will be available for non-commercial scientific purposes.

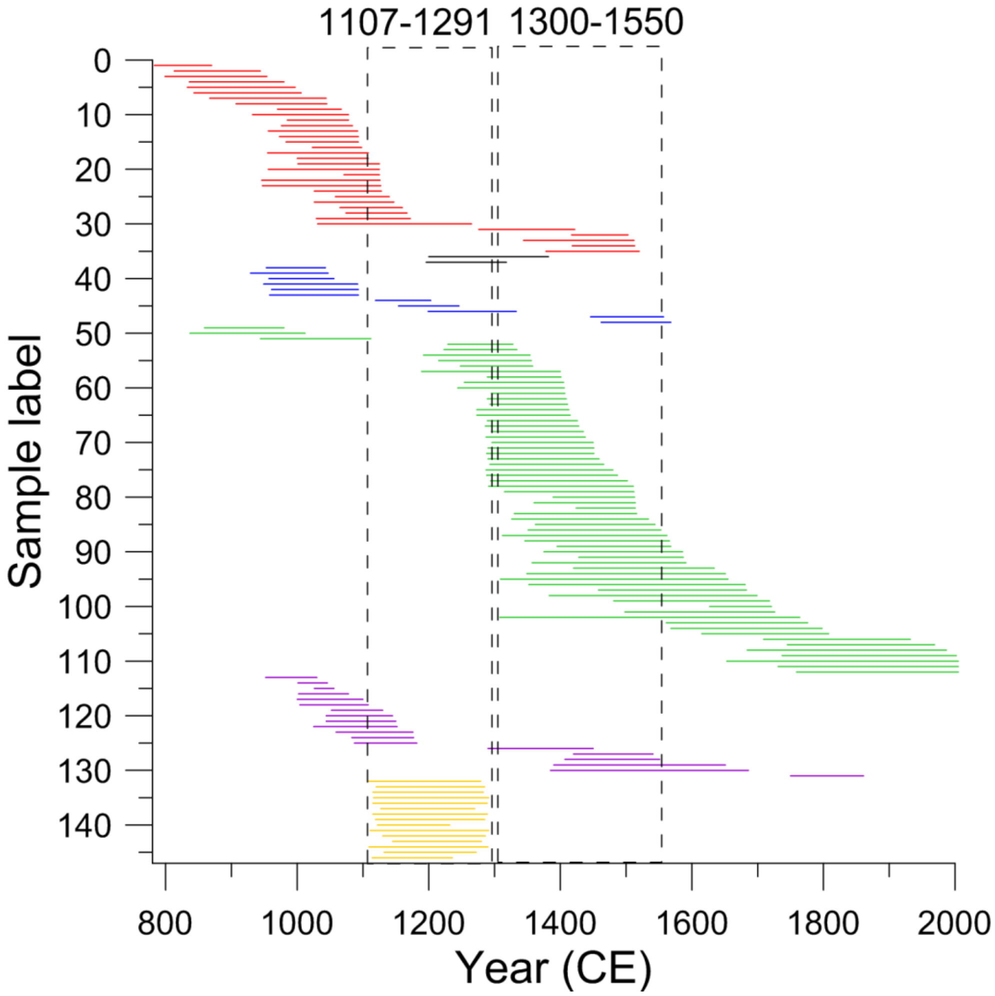

Figure ~~S1~~A.1. *The time spans of the samples from Håckervalen-south (red), Jens Perstjärnen (black), Ö Helgtjärnen (blue), Furuberget-north (green), Lilla-Rörtjärnen (purple) and Bodsjö (yellow). The samples from Furuberget-north which are fully or partly covering the period 1300-1550 are used as references for adjusting the mean values of the samples from Håckervalen-south, Jens Perstjärnen, Ö Helgtjärnen and Lilla-Rörtjärnen. The samples from Furuberget-north and the adjusted samples from Håckervalen-south, Jens Perstjärnen, Ö Helgtjärnen and Lilla-Rörtjärnen which are fully or partly covering the period 1107-1291 are used as references for adjusting the mean values of the samples from Bodsjö.*

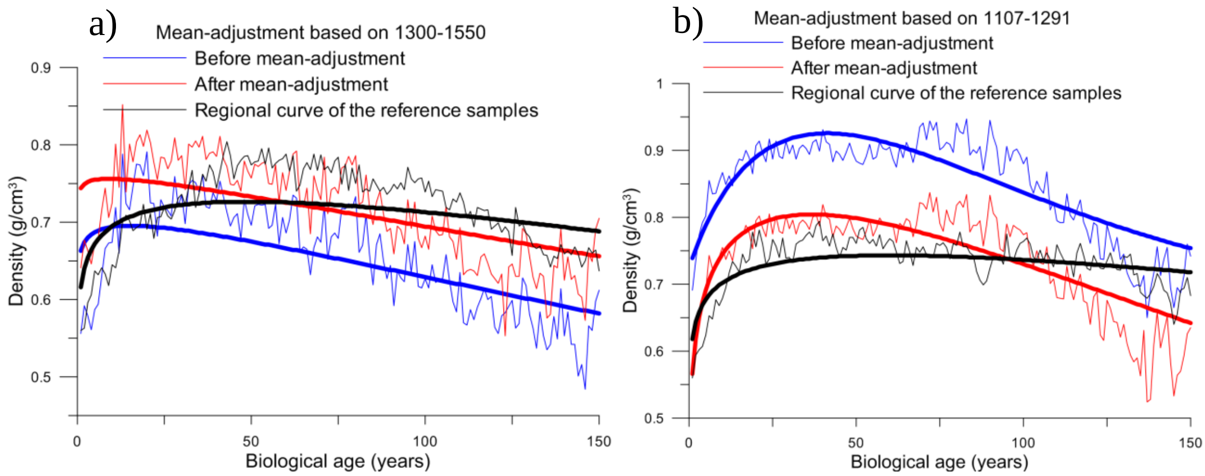

Figure ~~S2~~A.2. *(a) The smoothed (bold) and unsmoothed (thin) average growth curves of the referenced samples (from Furuberget-north, black) and the samples (from Håckervalen-south, Lilla-Rörtjärnen, Ö Helgtjärnen and Jens Perstjärnen) before (blue) and after (red) mean-adjustment in the common period (1300-1550), (b) the same as (a) but for the mean-adjustment of the historical building samples over the period 1107-1291.*

***Table A.1** Mean age statistics of the reference and mean-adjusted samples*

Common period	Site	Number of samples	Mean start age	Mean end age	Mean age
1300-1550	Furuberget-north (reference)	50	33	176	105
	Håckervalen-south	5	40	162	101
	Ö Helgtjärnen	3	52	127	90
	Lilla-Rörtjärnen	5	12	160	86
	Jens Perstjärnen	2	128	178	153
1107-1291	In-situ sites (reference)	42	51	89	70
	Bodsjö (historical building)	15	1	158	79

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References

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Björklund, J. A., Gunnarson, B. E., Krusic, P. J., Grudd, H., Josefsson, T., Östlund, L., and Linderholm, H. W.: Advances towards improved low-frequency tree-ring reconstructions, using an updated Pinus sylvestris L. MXD network from the Scandinavian Mountains, *Theoretical and applied climatology*, 113(3-4), 697-710, 2013.

Björklund JA, Gunnarson BE, Seftigen K, Esper J, Linderholm HW (2014a) Blue intensity and density from Northern Fennoscandian tree rings: using earlywood information to improve reconstructions of summer temperature. Clim Past 10:877–885.

Björklund JA (2014b) Tree-rings and climate: standardization, proxydevelopment, and Scandinavian summer temperature history. PhD thesis. Department of Earth Sciences, University of Gothenburg.

Björklund, J., Gunnarson, B. E., Seftigen, K., Zhang, P., & Linderholm, H. W. (2015). Using adjusted Blue Intensity data to attain high-quality summer temperature information: A case study from Central Scandinavia. The Holocene, 25(3), 547-556.

Bojariu R. and Giorgi F.: The North Atlantic Oscillation signal in a regional climate simulation for the European region, *Tellus A*, 57(4), 641-653, 2005.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlen, W., Zetterberg, P., and Eronen, M.: Fennoscandian summers from AD 500: temperature changes on short and long timescales, *Climate Dynamics*, 7(3), 111-119, 1992.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., Karlén, W., and Shiyatov, S. G.: Tree-ring variables as proxy-climate indicators: problems with low-frequency signals, in: Climatic variations and forcing mechanisms of the last 2000 years, Springer, 9-41, 1996.

Briffa, K. R., T. J. Osborn, F. H. Schweingruber, I. C. Harris, P. D. Jones, S. G. Shiyatov, and E. A. Vaganov (2001), Low-frequency temperature variations from a northern tree ring density network. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 106(D3), 2929-2941.

~~Briffa, K. R., Osborn, T. J., Schweingruber, F. H., Jones, P. D., Shiyatov, S. G., and Vaganov, E. A.: Tree-ring width and density data around the Northern Hemisphere: Part 1, local and regional climate signals, *The Holocene*, 12(6), 737-757, 2002.~~

Busuioc, A., Chen, D., Hellström, C., 2001. Temporal and spatial variability of precipitation in Sweden and its link with the large scale atmospheric circulation. Tellus. 53A, 348–367.

Chen, D. and Hellström, C.: The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations, *Tellus A*, 51(4), 505-516, 1999.

Cook, E. R. and Peters, K.: The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree-Ring Bulletin*, 41, 45-53, 1981.

Cook, E. R., Briffa, K. R., Meko, D. M., Graybill, D. A., and Funkhouser, G.: The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies, *The Holocene*, 5(2), 229-237, 1995.

Cook, E. R., Krusic, P. J., and Melvin T.: Program RCSsigFree: Version 45_v2b. Lamont-Doherty Earth Obs. Columbia University, 2014.

Esper, J., Frank, D. C., Timonen, M., Zorita, E., Wilson, R. J., Luterbacher, J., Holzkämper, S., Fischer, N., Wagner, S., and Nievergelt, D.: Orbital forcing of tree-ring data, *Nature Climate Change*, 2(12), 862-866, 2012.

Folland, C.K., Knight, J., Linderholm, H.W., et al., 2009. The summer North Atlantic Oscillation: past, present, and future. Journal of Climate. 22(5), 1082–1103.

Frank, D., J. Esper, E. Zorita, and R. Wilson (2010), A noodle, hockey stick, and spaghetti plate: a perspective on high-resolution paleoclimatology. *Wiley Interdisciplinary Reviews: Climate Change*, 1(4), 507-516.

Fritts, H.: Tree rings and climate, Academic Press, London, 1976.

George, S. S. (2014). An overview of tree-ring width records across the Northern Hemisphere. Quaternary Science Reviews, 95, 132-150.

~~Gonzalez-Rouco, J. F., Fernández-Donado, L., Raible, C. C., Barriopedro, D., Lutherbacher, J., Jungclaus, J. H., ... & Ammann, M. (2011). Medieval Climate Anomaly to Little Ice Age transition as simulated by current climate models.~~

~~Goosse, H., Crespin, E., Dubinkina, S., Loutre, M. F., Mann, M. E., Renssen, H., ... & Shindell, D. (2012). The role of forcing and internal dynamics in explaining the "Medieval Climate Anomaly". Climate dynamics, 39(12), 2847-2866.~~

Gordon G (1982) Verification of dendroclimatic reconstructions. In Climate from tree rings, Hughes MK, Kelly PM, Pilcher JR, LaMarche VC, Jr (eds). Cambridge University Press: Cambridge: 58–61

Graham, R., Robertson, I., McCarroll, D., Loader, N., Grudd, H., and Gunnarson, B.: Blue Intensity in Pinus sylvestris: application, validation and climatic sensitivity of a new palaeoclimate proxy for tree ring research, *AGU Fall Meeting Abstracts*, 2011.

Grove, J. M.: The initiation of the "Little Ice Age" in regions round the North Atlantic, in: *The Iceberg in the Mist: Northern Research in pursuit of a "Little Ice Age"*, Springer, 53-82, 2001.

Grove, J. M. and Switsur, R.: Glacial geological evidence for the Medieval Warm Period, *Climatic Change*, 26(2-3), 143-169, 1994.

Grudd, H., Briffa, K. R., Karlén, W., Bartholin, T. S., Jones, P. D., and Kromer, B.: A 7400-year tree-ring chronology in northern Swedish Lapland: natural climatic variability expressed on annual to millennial timescales, *The Holocene*, 12(6), 657-665, 2002.

Gunnarson, B. E.: Temporal distribution pattern of subfossil pines in central Sweden: perspective on Holocene humidity fluctuations, *The Holocene*, 18(4), 569-577, 2008.

Gunnarson, B. E., Borgmark, A., and Wastegård, S.: Holocene humidity fluctuations in Sweden inferred from dendrochronology and peat stratigraphy, *Boreas*, 32(2), 347-360, 2003.

Gunnarson, B. E., Linderholm, H. W., and Moberg, A.: Improving a tree-ring reconstruction from west-central Scandinavia: 900 years of warm-season temperatures, *Climate Dynamics*, 36(1-2), 97-108, 2011.

Gunnarson, B. E., Josefsson, T., Linderholm, H. W., and Östlund, L.: Legacies of pre-industrial land use can bias modern tree-ring climate calibrations, *Climate Research*, 53(1), 63-76, 2012.

Harris, I., Jones, P., Osborn, T., and Lister, D.: Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset, *International Journal of Climatology*, 34(3), 623-642, 2014.

Helama, S., Lindholm, M., Timonen, M., Meriläinen, J., and Eronen M.: The supra-long Scots pine tree-ring record for Finnish Lapland: Part 2, interannual to centennial variability in summer temperatures for 7500 years, *The Holocene*, 12(6), 681-687, 2002.

Helama S, Mielikäinen K, Timonen M and Eronen M, 2008. Finnish supra-long tree-ring chronology extended to 5634 BC. Norwegian Journal of Geography 62(4): 271–277, DOI 10.1080/00291950802517593.

Helama, Samuli, Marc Macias Fauria, Kari Mielikäinen, Mauri Timonen, and Matti Eronen. "Sub-Milankovitch solar forcing of past climates: mid and late Holocene perspectives." Geological Society of America Bulletin 122, no. 11-12 (2010): 1981-1988.

Helama, S., Vartiainen, M., Holopainen, J., Mäkelä, H. M., Kolström, T., and Meriläinen J.: A palaeotemperature record for the Finnish Lakeland based on microdensitometric variations in tree rings, *Geochronometri*a, 41(3), 265-277, 2014.

Irannezhad, M., Chen, D., & Kløve, B. (2014). Interannual variations and trends in surface air temperature in Finland in relation to atmospheric circulation patterns, 1961–2011. International Journal of Climatology.

Johannessen T. W.: The climate of Scandinavia. Climates of Northern and Western Europe. *World survey of climatology*, 5, 23-80, 1970.

Johansson B. and Chen D.: The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling. *International Journal of Climatology*, 23, 12, 1523-1535, 2003.

Lamb, H. H. : Climatic fluctuations. *World survey of climatology*, 2, 173-249. 1969

Linderholm H W, Solberg B Ø, and Lindholm M.: Tree-ring records from central Fennoscandia: the relationship between tree growth and climate along a west–east transect. *The Holocene*, 13(6): 887-895, 2003.

Linderholm, H~~. W., & Gunnarson, B. E. (2005). Summer temperature variability in central Scandinavia during the last 3600 years. Geografiska Annaler: Series A, Physical Geography, 87(1), 231-241.~~

~~Linderholm, H~~., Björklund, J., Seftigen, K., Gunnarson, B. E., Grudd, H., Jeong, J.-H., Drobyshev, I., and Liu, Y.: Dendroclimatology in Fennoscandia–from past accomplishments to future potential, *Climate of the Past*, 6, 93–114, 2010.

Linderholm, H. W., Zhang, P., Gunnarson, B. E., Björklund, J., Farahat, E., Fuentes, M., Rocha, E., Salo, R., Seftigen, K., and Stridbeck P.: Growth dynamics of tree-line and lake-shore Scots pine (Pinus sylvestris L.) in the central Scandinavian Mountains during the Medieval Climate Anomaly and the early Little Ice Age, *Frontiers in Ecology and Evolution: Paleoecology*, 2, 20, 2014.

Linderholm, H., Björklund, J., Seftigen, K., Gunnarson, B., and Fuentes M.: Fennoscandia revisited: a spatially improved tree-ring reconstruction of summer temperatures for the last 900 years, *Climate Dynamics*, 45:933–947, 2015.

Lundqvist, J.: Beskrivning till jordartskarta över Jämtlands län: 4 Karten. Kt, Sveriges Geologiska Undersökning, 1969.

J Luterbacher, J P Werner, J E Smerdon, L Fernández-Donado, F J González-Rouco, D Barriopedro, F C Ljungqvist, U Büntgen, E Zorita, S Wagner, J Esper, D McCarroll, A Toreti, D Frank, J H Jungclaus, M Barriendos, C Bertolin, O Bothe, R Brázdil, D Camuffo, P Dobrovolný, M Gagen, E García-Bustamante, Q Ge, J J Gómez-Navarro, J Guiot, Z Hao, G C Hegerl, K Holmgren, V V Klimenko, J Martín-Chivelet, C Pfister, N Roberts, A Schindler, A Schurer, O Solomina, L von Gunten, E Wahl, H Wanner, O Wetter, E Xoplaki, N Yuan, D Zanchettin, H Zhang and C Zerefos: European summer temperatures since Roman times, Environmental Research Letters, 11(2), 2016, doi: 10.1088/1748-9326/11/2/024001

~~Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., ... & Ni, F. (2009). Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science, 326(5957), 1256-1260.~~

Matskovsky, V. V. and Helama, S.: Testing long-term summer temperature reconstruction based on maximum density chronologies obtained by reanalysis of tree-ring data sets from northernmost Sweden and Finland. *Climate of the Past*, 10(4), 1473-1487, 2014.

McCarroll, D., Loader, N. J., Jalkanen, R., Gagen, M. H., Grudd, H. Gunnarson, B. E., Kirchhefer, A. J., Friedrich, M., Linderholm, H. W., and Lindholm, M.: A 1200-year multiproxy record of tree growth and summer temperature at the northern pine forest limit of Europe, *The Holocene*, 23(4), 471-484, doi:10.1177/0959683612467483, 2013.

Melvin, T. M.: Historical growth rates and changing climatic sensitivity of boreal conifers, PhD Thesis, Climatic Research Unit, University of East Anglia, UK, 271 pp., 2004.

Melvin, T. M. and Briffa, K. R.: A “signal-free” approach to dendroclimatic standardisation, *Dendrochronologia*, 26(2), 71-86, 2008.

Melvin, T. M., Grudd, H., and Briffa, K. R.: Potential bias in ‘updating’ tree-ring chronologies using regional curve standardisation: Re-processing 1500 years of Torneträsk density and ring-width data, *The Holocene*, 23(3), 364-373, 2013.

Melvin, T. M., Briffa, K. R.: CRUST: Software for the implementation of regional chronology standardisation: part 1. Signal-free RCS. *Dendrochronologia*, 32(1): 7-20, 2014a.

Melvin, T. M., Briffa, K. R.: CRUST: Software for the implementation of Regional Chronology Standardisation: Part 2. Further RCS options and recommendations. *Dendrochronologia*, 32(4): 343-356, 2014b.

National Research Council. 2006. Surface Temperature Reconstructions for the Last 2,000 Years. The National Academies Press: Washington, DC, 160 pp

van Oldenborgh, G. J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., Hazeleger, W., and Dijkstra, H.: Western Europe is warming much faster than expected, *Climate of the Past*, 5, 1–12, doi:10.5194/cp-5-1-2009, 2009.

PAGES 2k Consortium: Continental-scale temperature variability during the last two millennia. *Nature Geoscience*, 6, 339-346, doi:10.1038/ngeo1797, 2013.

Rodwell, M. and Folland, C.: Atlantic air–sea interaction and seasonal predictability, Quarterly *Journal of the Royal Meteorological Society*, 128(583), 1413-1443, 2002.

Rodwell, M., Rowell, D. and Folland, C.: Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature*, 398(6725), 320-323, 1999.

Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.: IPCC, 2013: summary for policymakers, in: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to *the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, UK, 3–29, 2013.

Tuomenvirta, H., Drebs, A., Forland, E., Tveito, O. E., Alexandersson, H., Laursen, E. V., and Jonsson, T.: Nordklim data set 1.0—description and illustrations, *DNMI Report*, 27, 2001.

Wallén, C. C. (ed.) Climates of Northern and Western Europe. Elsevier, Amsterdam, 1970.

Wigley, T. M., Briffa, K. R., and Jones, P. D.: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *Journal of Climate and Applied Meteorology*, 23(2), 201-213, 1984.

Wilson RJS, Anchukaitis K, Briffa K, Büntgen U, Cook ER, D'Arrigo R, Davi N, Esper J, Frank D, Gunnarson B, Hegerl G, Helama S, Klesse S, Krusic PJ, Linderholm HW, Myglan V, Osborn T, Rydval M, Schneider L, Schurer A, Wiles G, Zhang P, Zorita E: Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context. Quaternary Science Reviews, 134, 1-18, 2016.

Yang, B., Qin, C., Wang, J., He, M., Melvin, T. M., Osborn, T. J., & Briffa, K. R. (2014). A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. Proceedings of the National Academy of Sciences, 111(8), 2903-2908.

Zhang, P., Björklund, J. and Linderholm, H.W.:. (2015): The influence of elevational differences in absolute maximum density values on regional climate reconstructions. *Trees*, 1-13. doi: 10.1007/s00468-015-1205-4, 2015.