

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

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Abstract. ~~An improved and extended *Pinus sylvestris* L. (Scots Pine)~~

~~New collected Scots pine (*Pinus sylvestris* L.) tree-ring maximum density (MXD) chronology from the central Scandinavian Mountains was used to reconstruct samples were used to replace the historical samples used in the previous central Scandinavia warm-season (April–September) temperature reconstruction, and to extend the reconstruction back to 850 CE. Due to systematic bias from differences in elevation (or local environment) of the samples through time, the data was “mean adjusted” Since the new samples are collected from different elevations, and the samples from the different elevations do not cover the same period, the mean value of the samples was adjusted. The new reconstruction, called C-Scan, was based on the RSFi standardisation method to was produced based on “regional curve adjusted individual signal-free approach” (RSFi) which preserve mid- and long-term climate variability signal, and has better potential to remove unwanted noise (e.g. related to stand dynamics) on tree level. The new reconstruction, called C-Scan, explaining more than 50% suggests lower temperature during Medieval Climate Anomaly (MCA) and higher temperature during Little Ice Age (LIA) than the previous reconstruction. The two reconstructions show coherent variability at multidecadal to century timescales during the period 1300–2000 % of the warm-season temperature variance in a large area of Central Fennoscandia, CE. Before 1300 CE, the two reconstructions show discrepancy especially for 1200–1250 CE. Comparing two independent summer temperature reconstructions from the northern Fennoscandia, C-Scan shows regional differences in temperature evolution at multidecadal to century timescales during MCA. The new reconstruction agrees with the general profile of Northern northern Hemisphere temperature evolution during the last 12 centuries, supporting the occurrences of a Medieval Climate Anomaly (MCA) around indicating the warm peak of MCA ca. 1009–1108 CE and a Little Ice Age (LIA) as the coldest period of LIA ca. 1550–1900 CE in Central Fennoscandia. C-scan suggests a later onset of LIA and a larger cooling trend during 1000–1900 CE than previous MXD-based reconstructions from Northern Fennoscandia. Moreover, during the last central Fennoscandia. Moreover, in central Fennoscandia,~~

during the past 1200 years, the coldest period was found in the late 17th–19th centuries-century with the coldest decades being centered on 1600 CE, and the warmest 100 years occurring in the most recent century.

1 Introduction

30 Fennoscandia has a strong tradition in dendrochronology, and its large tracts of boreal forest make the region well suited for the development of tree-ring chronologies that extend back ~~several thousands~~
of years-over the last millennium (Linderholm et al., 2010). In addition to the well-known multi-
millennial tree-ring width chronologies from Torneträsk (Grudd et al., 2002), Finnish Lapland (Helama
et al., 2002) and Jämtland (Gunnarson et al., 2003), several millennium long temperature-sensitive
35 tree-ring datasets were collected within the European Union funded “~~Millennium~~”-“Millennium” project
(McCarroll et al., 2013). However, these ~~are-were~~ all, except for the Jämtland and Mora (822 year
Blue intensity, Graham et al., 2011) records, located in northernmost Fennoscandia. It has been
shown that in order to better represent Fennoscandian warm-season temperature variability, data
from more southern locations are needed (Linderholm et al., 2014a). ~~Thus, getting high-quality~~
40 ~~data from the central parts of Fennoscandia is needed.~~ More recently, Helama et al. (2014) recon-
structed May–September temperature variability in southern Finland (around 61° N) for the last
millennium using maximum latewood density (MXD) data. In Sweden, ~~presently~~ the southernmost
site to provide a ~~robust~~ temperature signal from tree-ring MXD data is the central Scandinavian
Mountains, in the province of Jämtland, where Gunnarson et al. (2011, henceforth G11, referring to
45 the temperature reconstruction) reconstructed 900 years of warm-season temperatures. Because of
the relatively southerly location, Jämtland is considered a key location for paleotemperature studies
in Scandinavia. Not only can it function as a link between chronologies in northern Fennoscandia
and those in continental Europe (Gunnarson et al., 2011), but also the closeness to the North Atlantic
makes it a suitable place to investigate long-term associations between marine and terrestrial climate
50 variability (e.g., Cunningham et al., 2013).

At northern high latitudes, MXD ~~and the newly developed Δ Density parameter are the~~ is the
most powerful warm-season temperature tree-ring ~~proxies, compared to tree-ring widths (Briffa et~~
~~al., 2002; Björklund et al. 2014)~~ proxy (Briffa et al., 2002a, b). The longest ~~MXD records are found~~
Scots pine MXD records have been sampled in northernmost Fennoscandia

55 ~~(see McCarroll et al., 2013; Melvin et al., 2013; Esper et al., 2012)~~
(see McCarroll et al., 2013; Melvin et al., 2013; Esper et al., 2012, 2014; Matskovsky and Helama, 2014).
These chronologies are exclusively based on material with known ~~temperature sensitive~~ temperature-sensitive
provenience, from living trees, ~~dry deadwood snags~~ and, in the case of N-Scan, subfossil wood
~~(Esper et al., 2012). The (tree remains which have been buried in lake sediments for hundreds or~~
60 thousands of years) (Esper et al., 2012). G11, however, also included ~~historical material (tree-ring~~

~~samples data collected from historical buildings). The historical samples were collected from buildings in in the Jämtland in the region in the late 1980s , as a part of a grand sampling strategy to focus on a dense tree-ring density network from an archaeological survey by Kwartärbiologiska Laboratoriet in Lund, Sweden. Subsequently MXD was derived from some of these samples, which were later included in a dense MXD network covering cool moist regions (Schweingruber et al., 1992) in the Northern Hemisphere (Schweingruber et al., 1990). Due to the limited number of deadwood samples dead wood samples at that time from the studied area in the Scandinavian Mountains, the historical samples , belonging to (covering the period between 1107 CE and 1827 CE, with a gap between 1292–1315 CE), made up the a major part of the G11 reconstruction. Since the geographical origin origins of the historical samples is unclear, it was difficult to fully assess the validity of the interpreted temperature signal. Comparing G11 to the Fennoscandian June–August summer temperature reconstruction from (Gouirand et al., 2008), a coherency was found between AD 1300 and 1900, but G11 showed a stronger warming between AD 1100 and 1300. One explanation for the differences between the two records could be regional differences in the temporal evolution of warm-season temperatures in central and northern Scandinavia (Gunnarson et al., 2011). For instance, Gunnarson and Linderholm (2002) suggested that the Medieval Climate Anomaly (MCA, 10th–13th are somewhat unclear, where they likely originate from lowland locations about 300 CE, Grove and Switsur, 1994) was of shorter duration but more pronounced in the meters below the present tree-line, it is not an optimal dataset to incorporate in a temperature reconstruction.~~

The Medieval Climate Anomaly (MCA, ca. 10th–13th CE, Grove and Switsur, 1994) is a period when the climate conditions in some regions are analogue to current warming, but without strong influences from human activities (Mann et al., 2009). This is a key period to evaluate if current warming can be reached without anthropogenic influences (Crowley and Lowery , 2000; Broecker , 2001). However, there are few high-quality, annually resolved temperature reconstructions covering the MCA in the world (Mann et al., 2009; PAGES 2k Consortium , 2013). In the central Scandinavian Mountains compared to Northern Scandinavia. Another reason for this apparent difference in late-MCA temperatures could be that the tree-ring samples collected from the historical buildings do not truly reflect summer temperature variability in the mountains due to their likely low-elevation origins data has shown excellent potential for reconstructing warm-season temperatures several centuries to millennia back in time (Linderholm and Gunnarson , 2005; Gunnarson et al., 2011). However, so far, the only MXD based temperature reconstruction from this region, G11, did not cover the whole MCA due to a lack of samples during this period.

~~To overcome this uncertainty, we developed a~~ Considering that 1) Jämtland is identified as a key dendroclimatological location in the Fennoscandian region, and 2) the fact that it does not cover the MCA in combination with 3) the questionable historical material of G11, the aim of this study is to extend the G11 temperature reconstruction and remove uncertainties of sampling provenances in the same. This will enable us to improve the understanding of the warm-season (April through

September) temperature reconstruction for the last temperature evolution during the entire past
1200 years based exclusively on Scots pine samples from sites close to the current altitude timber line
100 in a relatively limited area. Since there was an elevational difference in the temporal distribution of
the samples, we also considered the impact of the temperature lapse rate and local environment on
MXD values, and corrected the MXD values according to the mean-adjustment method (Zhang in review).
Furthermore, the traditional RCS (regional curve standardisation) method (Briffa et al., 1992) was
compared with the new RSi (regional curve adjusted individual signal-free approach) method
105 (Björklund et al., 2014) when developing the chronology in this region, as well as make a more
reliable comparison between the MCA and present conditions.

2 Data and method

2.1 Study area

The province of Jämtland is located in the westernmost part of central Sweden (Fig. 1). The region
110 belongs to the ~~Northern Boreal~~ northern boreal zone, and the study area is situated just east of the
Scandinavian Mountains main divide. The main topography ranges from 800 to 1000 m a.s.l., ~~but~~
and scattered alpine massifs to the south reach approximately 1700 m a.s.l. There is a distinct cli-
mate gradient in the area (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 moun-
115 tains in the west, and the ~~east-west~~ east-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 located in a border zone between oceanic and continental climates
(Wallén, 1970). On short timescales, summer climate of this particular region is influenced by the
atmospheric circulation, mainly the North Atlantic Oscillation (NAO) (Chen and Hellström, 1999),
120 while it is affected by North Atlantic sea-surface temperature (SST) on longer timescales (Rodwell
et al., 1999; Rodwell and Folland, 2002).

Glacial deposits dominate the area, mainly till but also glaciifluvial deposits, peatlands and small
areas of lacustrine sediments (Lundqvist, 1969). The forested parts in the central Scandinavian
Mountains are dominated by ~~*Pinus sylvestris* L. (Scots Pine), Scots pine, Norway spruce (*Picea*~~
125 ~~*abies* (Norway spruce) and (L.) H. Karst.) and mountain birch (*Betula pubescens* (Mountain birch,~~
Ehrh.)). Although large-scale forestry have been carried out in most parts of the county, the human
impact on trees growing close to the tree line is limited, which is valuable in tree-ring based climate
reconstructions (Gunnarson et al., 2012). Due to the short and cool summers, ~~dry deadwood snags~~
can be preserved for more than 1000 years (Linderholm et al., 2014b). Moreover, large amounts of
130 subfossil wood from hundreds to thousands of years ago can be found in small mountain lakes (see
Gunnarson, 2008).

2.2 Tree-ring data and data statistics

The tree-ring data used in this study ~~came from 8~~ was sampled at eight sites (Table 1). As shown in Fig. 1, they are all ~~at a close distance~~ in close proximity to each other, but differ in elevation and local environment. From the small peak Furuberget, 142 samples were collected close to the top at 135 ca. 650 m a.s.l. in an open pine forest with limited ~~competition~~ competitions between trees. Pine trees grow on a relatively flat area covered by a thick vegetation layer with woody dwarf shrubs and mosses. The area is characterized by thin till and glacial soils. 35 of these samples were included in G11 (Table 1). In addition, pine samples were collected at different elevations on Mount 140 Håckervalen from the present tree line (at around 650 m a.s.l.) up to 800 m a.s.l., described in detail in Linderholm et al. (2014b). ~~At both sites living trees and dry deadwood were sampled.~~ Samples preserved in lakes (~~so-called~~ subfossil wood) were included from the lakes Lill-Rörtjärnen, Östra Helgtjärnen and Jens-Perstjärnen, ~~previously and have previously been~~ described in Gunnarson (2008). The historical tree-ring data, collected from historical buildings in the province was down- 145 loaded from the International Tree-Ring Data Bank (~~ONLINE RESOURCE: ITRDB~~).

The new MXD ~~measurements samples~~ (Table 1) were ~~produced measured~~ using an ITRAX ~~Wood wood~~ scanner from Cox Analytic System (<http://www.coxsys.se>). ~~For further information of the ITRAX settings, see Gunnarson et al. (2011). The historical samples was collected by Schweingruber et al. in the 1970 (Schweingruber et al., 1991) and the MXD measurements was obtained using the DENDRO2003 x-ray instrumentation from Walesch Electronic (http://www.walesch.ch/). All samples were prepared according to standard dendrochronological techniques (Schweingruber et al., 1978).~~ All the tree-ring samples were prepared according to Schweingruber et al. (1978). Thin laths (1.20 mm thick) were cut from each sample using a twin-bladed circular saw and subsequently resins and other compounds were extracted with pure alcohol in a Soxhlet apparatus. After being extracted for at least 24 hours, the laths were acclimatized in a room with controlled temperature and humidity to 12 % water content, and were then mounted in a sample holder. The samples were then exposed to a narrow, high energy, X-ray beam. The chrome tube in the ITRAX was tuned to 30 kV and 50 mA, with 75 ms steptime. The opening time of the sensor slit was set to 20 m at each step. From the detected X-ray radiation a 16-bit, greyscale, digital image with a resolution of 1270 dpi was captured. The grey levels were calibrated to values of wood density using a cellulose acetate calibration wedge provided by Walesch Electronics. The tree-ring MXD data were analysed with the image processing software WinDENDRO. 150 160

~~It was previously found that in the studied region, the absolute MXD values differ with respect to elevation, which is likely~~ In Zhang et al. (2015), it was found that the MXD data used in this study, originating from various altitudes (Table. 1), likely differ in their mean values due to the ~~temperature lapse rate (Zhang in review)~~ environmental temperature lapse rates. In short, the ~~absolute~~ MXD values at higher elevation ~~are~~ were found to be systematically lower than those from lower elevation. Moreover, ~~the elevation effect on the absolute MXD values is~~ this influence on the MXD

~~values was found to be~~ larger than the ~~effect of~~ temperature differences between warm (MCA) and
170 ~~cold (Little Ice Age, LIA, 14th–19th centuries Grove, 2001) periods. Thus, an average chronology~~
~~with a heterogeneous elevational sample distribution through time, e. g. older the cold Little Ice~~
~~Age (LIA, 14th–19th century according to Grove (2001)). Consider for example that older deadwood~~
samples are found only at progressively higher elevations, ~~will contain systematic differences in their~~
~~means during different periods~~ even above present day tree line, as in Linderholm et al. (2014b), and
175 ~~that these samples are combined with lower elevation living trees and younger deadwood.~~ If not
~~attended to accounted for,~~ this may introduce ~~serious~~ biases to an ~~average averaged~~ chronology, both
in terms of the ~~high-resolution variability (annual to decadal) and the long-term trend. It is evident~~
~~from Fig. 2, that there are periods when the samples from different elevations do not overlap in~~
~~time, e. g. 1550–1800 (no samples from Håckervalen-top and Furuberget 1 overlap.). To overcome~~
180 ~~this problem~~ variability, but perhaps even more so in the longer-term trends (Zhang et al., 2015).
~~Therefore,~~ we adjusted the mean MXD ~~value values~~ from the different elevations to have the same
mean during a period of overlap ~~following the recommendations of Zhang et al. (2015).~~ The mean
MXD value of the ~~Furuberget 1–Furuberget-north~~ samples, covering 1300–1550 CE, was used as
a reference ~~to adjust the for the adjustment of~~ samples from other groups ~~except for the sites Håckervalen~~
185 ~~and Furuberget 2 (samples from these two groups do not cover 1300–1550). A constant was added to~~
~~or subtracted from each sample of a group in order to force the samples to have the same mean MXD~~
~~value as the reference. Since the living trees from Håckervalen (650) and Furuberget 2 have the~~
~~same elevation as Furuberget 1, and both of the sites do not have significantly different mean MXD~~
~~values with the Furuberget 1 samples during 1800–2000, we did not adjust the samples from these~~
190 ~~two sites. We chose Furuberget 1 as . The choice of Furuberget-north as~~ a reference site ~~, because~~
~~the Furuberget 1 samples had~~ ~~was based on the criteria of~~ a high sample replication and a wide
temporal coverage. ~~Other ways to deal with this problem is to standardise the samples site-by-site~~
~~(or group-by-group) rather than adjusting the mean value of each group of samples. However, this~~
~~method works well when all groups have the same or similar temporal distribution.~~

195 2.3 Standardisation ~~method~~ and chronology building

If tree-ring data is going to be used to attain reliable climate information, it is pertinent to remove
as much non-climatic information 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 (Fritts, 1976; Cook and
200 Peters, 1981), and subtracted or divided from each raw tree-ring measurement to obtain indices
used for chronology building, in a process termed standardisation. This approach is widely used, but
it severely limits the ~~attained preservation of~~ low-frequency variability in long chronologies (~~with~~
~~based on~~ several generations of trees), because ~~all indices have similar averages, the mean value of~~

all the tree-ring series will be adjusted to the same level after standardization. This is referred to as the “segment length curse” (Cook et al., 1995; Briffa et al., 1996).

This 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 subtracted from or divided by each individual tree-ring measurement, where this process is an approach called Regional Curve Standardisation (RCS; Briffa et al., 1992). However, by using one single function for all tree-ring series, less-unwanted mid-frequency noise (not climate-related signal) variability is not efficiently 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, 2008; Melvin and Briffa, 2014a, b). Melvin and Briffa (2014a, b) show that using multi-curve RCS can, however, efficiently remove these biases. Alternatively, the non-climatological expression in tree-ring data can be quantified with the an individual signal-free (SF) approach to standardisation, described in Melvin and Briffa (2008), either on individual trees or on an average of all trees (RCS). Using SF RCS can alleviate possible trend distortions, but limited noise from stand competition etc. is removed, but this approach is more limited in the lower most frequencies (Björklund et al., 2013).

By However, by using the SF individual fitting approach and at the same time letting the derived functions to have a similar mean as their 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 approach was termed RSFi (ibid.). We compared chronologies resulting from the above described method, a hybrid of the RCS and individual SF standardization is henceforth referred to as RSFi. We produced chronologies with the standardisation methods: classic RCS, SF RCS and (single curve and multi-curve) and RSFi, where the chronology used for reconstruction was derived with RSFi. RSFi chronology was used for the new reconstruction. The standardisations were performed with the software RCSsigFree (Cook et al., 2014) and CRUST (Melvin and Briffa, 2014a, b). 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). In this study, the EPS values were calculated in a 50-year temporal window with 25-year overlap.

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 of 1911–1979 CE, we extended the data back to 1890 CE and up to 2011 CE by using linear regression on monthly temperature data from an adjacent station: Östersund

240 (376 m a.s.l., 63.20° N, 14.49° E). A linear regression was done to relate mean temperature of each month from Östersund station to that from Duved station. Data from Östersund explain on average 91.5 % of the interannual variance in Duved monthly temperature (based on the overlapping period 1911–1979 CE). The temperature data from Östersund came from two sources: the Nordklim data base (1890–2001 CE) (Tuomenvirta et al., 2001), and Swedish Meteorological and Hydrological
245 Institute (SMHI, 2001–2011 CE). The locations of Duved and Östersund stations are shown in Fig. 1.

3 Warm-season temperatures reconstruction

2.5 Climate signal in the new chronology

We compared the new chronology with the instrumental monthly mean temperatures constructed for the Duved meteorological station during the period 1890–2011 CE. Fig. 3a shows that the new
250 chronology has a significant positive correlation (at $p < 0.01$ level) with individual monthly mean temperatures in April–September, and the highest correlation was found with mean April–September temperature ($r = 0.77$). Therefore, we decided to reconstruct the April–September mean temperature (henceforth referred to as warm-season temperature). The reconstructed and observed warm-season temperatures for 1890–2011 CE show a good agreement on interannual to multidecadal timescales
255 (Fig. 3c), and the new MXD reconstruction explains 59% of the variance in the instrumental data (Fig. 3b).

2.6 Reconstruction statistics

In order to test the temporal stability of the MXD vs. the instrumental observations, we divided the instrumental period into two parts: 1890–1950 CE and 1951–2011 CE, with the first part for
260 calibration and the second part for verification. Then, we switched the calibration and verification periods, and repeated the same exercise. The calibration and verification statistics are shown in Table 2. The reduction of error statistic (RE) has a possible range of $-\infty$ to 1, and an RE of 1 can be achieved only if the prediction residuals equal zero. Zero is commonly used as a threshold, and the positive RE values in the both calibration periods suggests that our reconstruction has some skill
265 (Table 2). Similar to RE, coefficient of efficiency (CE) is a measure to evaluate the model under the validation period. Values close to zero or negative suggests that the reconstruction is no better than the mean, whereas positive values indicate the strength and temporal stability of the reconstruction.

We evaluated the spatial representativeness of the new warm-season temperature reconstruction by correlating it with the CRU TS3.22 $0.5^\circ \times 0.5^\circ$ gridded warm-season temperature (Harris et al., 2014) for
270 the period 1901–2011 CE. We also compared the field correlation of observed warm-season temperature. As expected, Fig. 4 shows that the new reconstruction (4a) captures a large part of the patterns from the observations (4b). The reconstruction represents the warm-season temperature variation

with correlations above 0.71 across much of central Fennoscandia, which validates the good spatial representativeness of our reconstruction.

275 3 Result and discussion

3.1 Comparing MXD samples of different origin

~~After having adjusted the mean value of each group of samples, we compared the~~

We compared the two chronologies based on the “in situ” and historical samples respectively. Three standardisation methods were applied to build the chronologies. ~~Figure 3 Fig. 5~~ shows a comparison of the z scored (based on 1700–1800 CE) historical-sample chronology (HSC, blue curves) and the “in situ”- chronology (ISC, black curves) produced by the signal-free RCS (~~Fig. 3a5a~~), negative exponential function standardisation (~~Fig. 3b5b~~), and RSFi standardisation (~~Fig. 3e5c~~) methods. Clearly, the same features can be observed regardless of the standardisation methods: (1) on multidecadal scales, the HSC agrees quite well with ISC between 1300 CE and 1800 CE, but the HSC displays a smaller variance than the ISC; (2) between 1100 CE and 1300 CE, there is a notable disagreement between HSC and ISC. On interannual scale (based on 1st difference chronologies), the HSC ~~can~~ explain 34 % ~~variance of of variance in the~~ ISC during 1100–1300 CE, and explain 62 % of the variance during 1300–1800 CE. Moreover, it should be noted that the ~~50-window~~-EPS values fall below 0.85 for both chronologies during the 1160–1220 CE period. We tested boosting the ISC with the historical samples during 1100–1300. ~~The statistic results show that CE, but~~ the EPS of the boosted chronology during 1160–1210 ~~is CE was~~ still below 0.85, and the EPS during 1225–1265 ~~is CE was~~ even smaller than before boosting. Only the EPS during 1212–1222 CE changed from below 0.85 to above 0.85. Consequently, there was no significant improvement of the robustness of the ISC during 1100–1300 CE after including the historical samples.

295 3.2 The influence of standardisation method

~~At present~~

Presently, RCS and signal-free RCS (single- and multi-RCS curves) are the most favoured standardisation methods when building chronologies intended to have their long-term variability preserved. We examined the performances of the ~~two RCS methods and three above mentioned RCS methods as well as~~ the RSFi method. As shown in Fig. 46, the difference among the ~~three four~~ differently standardised chronologies is mainly reflected in the ~~multi-decadal-multidecadal~~ variability. The chronologies produced by the ~~both two single-curve~~ RCS methods are in very good agreement on ~~multi-decadal timescales. Although the RSFi chronology shows a similar evolution as the RCS ones, it is obvious that they differ in some periods. In general, the RSFi chronology~~ multidecadal timescales. The chronology produced by the multi-curve signal-free RCS methods differs from the ones based on single-curve RCS method, where it suggests warmer conditions over

the past 1200 year, especially during the periods 930–1000 CE, 1270–1520 CE and 1620–1900 CE. The RSFi chronology, in turn, differs from all the three RCS ones, and it suggests slightly warmer conditions than the single-curve RCS based ones, especially pronounced during the late half of LIA, and colder condition than the multi-curve signal-free RCS chronology, especially pronounced during 1270–1550 CE. It is ~~diffieult~~ impossible to firmly state which one of the chronologies is closer to actual temperatures, but we argue that there is a benefit in using individual signal-free curves (the RSFi method) rather than a common regional signal-free curve (~~the RCS methods~~) or multi regional signal-free curve, since this procedure has a better potential to remove unwanted noise (e.g. related to stand dynamics) on tree level. Consequently, we opted for the RSFi chronology for the reconstruction.

3.3 Climate signal in the new chronology ~~We compared the new chronology with the instrumental monthly mean temperatures constructed for the Duved meteorological station during the period 1890–2011. Figure 5a shows that the new chronology has a significant positive correlation (at $p < 0.01$ level) with individual monthly mean temperatures in April through September, and the highest correlation was found with mean April–September temperature ($r = 0.77$). Therefore, we decided to reconstruct the April–September mean temperature (henceforth referred to as Central Fennoscandian warm-season temperature). The reconstructed and observed warm-season temperatures for the 1890–2011 period show a good agreement on interannual to multidecadal timescales (Fig. 5c), and the new MXD reconstruction explains approximately 59 of the variance in the instrumental data (Fig. 5b): temperature evolution~~

3.4 The new reconstruction

~~In order to test the temporal stability of the MXD vs. observation when creating a model to reconstruct warm-season temperature back in time, we divided the instrumental period into two parts: 1890–1950 and 1951–2011, with the first part for calibration and the second part for verification. Then, we switched the calibration and verification periods, and repeated the same exercise. The calibration and verification statistics are shown in Table 2. The reduction of error statistic (RE) has a possible range of $-\infty$ to 1, and an RE of 1 can be achieved only if the prediction residuals equal zero. Zero is commonly used as a threshold, and the positive RE values in the both calibration periods suggests that our reconstruction has some skill (Table 2). Similar to RE, coefficient of efficiency (CE) is a measure to evaluate the model under the validation period. Values close to zero or negative suggests that the reconstruction is no better than the mean, whereas positive values indicate the strength and temporal stability of the reconstruction.~~

We evaluated the spatial representativeness of the new warm-season temperature reconstruction by correlating it with the CRU TS3.22 0.5 × 0.5 gridded warm-season temperature (Harris et al., 2014) for the period 1901–2011. The field correlation maps were plotted using the “KNMI climate explorer” (Royal Netherlands meteorological Institute; ; Van Oldenborgh et al., 2009). We also compared the field correlation of observed warm-season temperature. As expected, Fig. 6 shows that the new reconstruction (Fig. 6a) captures a large part of the patterns from the observations (Fig. 6b). The reconstruction represents the warm-season temperature variation with correlations above 0.71 across much of Central Fennoscandia, which validates the good spatial representativeness of our reconstruction.

4 Discussion

3.1 Central Fennoscandian warm-season temperature evolution

Figure 7 shows the reconstructed warm-season temperature of Central Fennoscandia in central Scandinavia, henceforth C-Scan, during the past 1200 years. C-Scan displays a cooling trend between 850 CE and 1800 CE, followed by a sharp temperature increase after the mid-19th century. In order to look at the C-Scan temperature evolution in more detail, we picked out the coldest and warmest periods (10, 30 and 100 years of mean temperatures respectively) during the last 1200 years (Fig. 7). The late 17th century to early 19th century was the coldest long-term period during the past 1200 years, and that the coldest 100-period-100-year period appeared during the 19th century. Both the coldest 10-and-30-10- and 30-year periods appeared during the 17th century. The warmest 100 years coincides with the most recent 100 years, which is consistent with the anthropogenic warming period (IPCC, 2013) (Stocker et al., 2013). However, the warmest 10-and-30-10- and 30-year periods were found in the 13th century. Comparing the MCA with the current warming period showed that the warmest 100-100-year period during the MCA was 0.1 °C cooler than the 20th century. The warmest 10-and-30-10- and 30-year periods during the 20th century were 0.2 °C and 0.1 °C cooler respectively than those during the 13th century. Despite low sample depth, the warmest 10-and-30-periods-have-51-10- and 30-year periods have EPS values above 0.85.

3.4 The influence on MXD of elevation differences

To highlight the application of mean-adjusted data in our reconstruction, we compared reconstructions based on mean-adjusted and unadjusted samples. As shown in Fig. 8, the reconstruction based on unadjusted samples (blue curve) yields a -0.4 °C lower average warm-season temperature during the period 850–1200 CE compared to the mean-adjusted reconstruction (black curve). Moreover, the long-term trend before the onset of the twentieth-12th century clearly differs between the two, where the cooling trend in the mean-adjusted data is turned to a warming trend in the unadjusted. Consequently, a reconstruction based on unadjusted data would indicate that warm-season temperature in

375 850–1200 CE, roughly corresponding to the MCA, would be about 0.3 °C cooler than the subsequent
four centuries (1201–1600 CE). This is ~~quite~~ contradictory to indications from other paleoclimate
data for Fennoscandia (e.g., Esper et al., 2012; McCarroll et al., 2013; Melvin et al., 2013; Helama et al., 2014)
(e.g., Esper et al., 2012; McCarroll et al., 2013; Melvin et al., 2013; Helama et al., 2014; Matskovsky and Helama, 2014),
as well as for the ~~whole Northern Hemisphere~~ extra-tropical northern hemisphere (Christiansen and Ljungqvist, 2012).
380 ~~Previous ways of dealing~~ A previous way to deal with samples of different origin (living trees, sub-
fossil and historical wood) ~~have used or different sites, has been to use~~ separate RCS curves for each
type of ~~samples (e.g., Gunnarson et al., 2011)~~ sample (Gunnarson et al., 2011; Esper et al., 2012), but
the prerequisite is that samples of different origin ~~are from the same periods~~ coexist in time, or at least
have a large overlap, so that any differences in long-term trend are to a large extent cancelled out
385 when averaging. Given that we did have some overlap between our different data, we could have
used the “separate RCS curves” method. However, although this method produces a similar recon-
struction after the mid-13th century, it ~~does deliver~~ provides a mean temperature for 850–900 CE
and 1150–1250 CE that is 0.2 °C lower than ~~that by our method. Therefore, we choose to use of the~~
~~mean-adjustment method.~~ by our preferred method.

390 3.5 Comparing C-Scan with ~~Northern Hemisphere temperature pattern and Northern~~ ~~Fennoscandia the previous central Scandinavia tree-ring~~ MXD ~~warm-season~~ ~~temperature reconstruction~~

To ~~set our new reconstruction in a wider context, we compared it with the Northern Hemisphere~~
~~temperature patterns based on multi-proxy records (Ljungqvist et al., 2012). Our new reconstruction~~
395 ~~shows an agreement with the general profile of Northern Hemisphere temperature evolution during~~
~~the last 12 centuries, supporting the occurrences of a MCA and LIA in Central Fennoscandia. The~~
~~hemisphere scale temperature patterns shows that, despite differences in-~~
C-Scan was compared with G11, and as shown in Fig. 9, the ~~onset of MCA or LIA phases~~
~~regionally, the Northern Hemisphere generally experience a relative warm period during 800–1300~~
400 ~~new~~ reconstruction suggests lower temperature during MCA and higher temperature during LIA than
the previous one. The two reconstructions show coherent variability at multidecadal to century
timescales during the period 1300–2000 CE. Before 1300 CE, the two reconstructions are less in
agreement, especially during 1200–1250 CE. This could be due to the low sample depth in C-Scan
at that time (see Fig. 7), but even though the sample depth was quite good in G11 during this period,
405 it still shows low inter-series correlation (see Fig. 4 in Gunnarson et al., 2011) which suggests a lack
of a coherent signal among the historical samples used in G11. The sample depth of C-Scan indicates
a mortality phase during 1100–1200 CE and a relative cold period during 1300–1900 following
a rather strong regeneration phase during 1200–1350 CE, and followed by an intensive warming
period after 1900. The strong regeneration of pine may result from successful establishment with

410 good seed production on ground where is dominated by vegetation complexes favorable for seedling
growth (Zachrisson et al., 1995).

3.6 Comparing C-Scan with two northern Fennoscandian summer temperature **reconstructions**

415 When comparing C-Scan with the most recently updated MXD reconstruction from northern Fennoscandia
(NFENNO, as shown in Fig. 10) (Matskovsky and Helama , 2014), the same feature is noted as in the
comparison with G11: consistent variability at multidecadal and century timescales after 1300 CE:
~~However, there are some aspects where our reconstruction shows differences. One such aspect is that~~
, except for 19th century, but less agreement before 1300 CE. It is clear that the low sample depth
causes the offset during the warmest century during MCA in our reconstruction occurred during
420 ~~the 11th century, while the Northern Hemisphere temperature peak is found in the 10th century.~~
~~Another aspect is that the cooling from MCA to the LIA seems to happen at a stable rate on~~
~~the hemisphere scale, while our reconstruction shows a weak cooling during the transition period~~
~~from the MCA to the LIA (1300–1500~~13th century, and hence, work on increasing the sample
depth of the period before 1300 CE), followed by an intensive cooling during the 16th century
425 ~~when central Scandinavia enter into a 300 cold-period. Globally, continental-scale temperature has~~
~~shown a regional~~CE is still needed in central Scandinavia. Another notable feature is that NFENNO
indicates higher summer temperatures in Northern Fennoscandia than that in central Scandinavia
during the 10th–11th centuries. When comparing C-Scan with the tree-ring multiproxy summer
temperature reconstruction from northern Fennoscandia (McCarroll et al., 2013), the latter suggests
430 a similar or slightly colder summer temperature in northern Fennoscandia than in central Scandinavia
during 10th–11th centuries. It is difficult to say which reconstruction in northern Fennoscandia
represents a true temporal evolution of summer temperature. However, the difference between central
and northern Fennoscandia may actually reflect a true difference in temporal evolution during the last
~~two millennia under natural forcings conditions (Ahmed et al., 2013). Thus, the lag of the warmest~~
435 ~~century during MCA and the late onset of LIA in central Fennoscandia can be explained by the~~
~~evolutions of summer temperature, which could be related to changes in the large-scale circulation~~
~~affecting the region. Possibly changes in the spatial positions of the nodes of the NAO dipole~~
~~over time (Ulbrich and Christoph , 1999; Zhang et al., 2008) could cause disruptions in the usually~~
~~coherent summer temperature pattern over Fennoscandia. Both reconstructed and observed surface~~
440 temperature evolutions show differences in their magnitudes in central and northern Scandinavia
in some time intervals during the last millennium (Ljungqvist et al., 2012) and the 20th century
(Diaz et al., 2011), which support the possibility of differences in regional temperature evolution.
~~However, considering the late onset of LIA, our reconstruction seems more similar with the temperature~~
~~evolution in North America and Australia rather than Arctic, Europe and Asia. Since the instrumental~~
445 record is too short, the mechanism behind this needs to be investigated, for example with assistance

of climate models. C-Scan also shows larger variance than the two summer reconstructions from northern Fennoscandia during some periods, and this is likely due to C-Scan being based on samples collected from a confined area, whereas the two northern reconstructions are from multi-sites in much larger areas.

450 ~~Zooming in to Fennoscandia, we compared~~

3.7 Comparing C-Scan with an extra-tropical northern hemisphere mean temperature reconstruction

C-Scan ~~to the MXD derived summer temperature reconstruction from northern Fennoscandia (N-Scan; Esper et al., 2012)~~ was also compared to the extra-tropical northern hemisphere (NH) multi-proxy annual mean temperature reconstruction from Christiansen and Ljungqvist (2012) in order to place it into a large spatial context. From Fig. 10a, it is clear that although our new reconstruction agrees well with the long-term cooling up until 1900, discussed by Esper et al. (2012), some obvious differences can be noted. The long-term cooling trend is slightly more pronounced in C-Scan (0.48 per 1000 over the period of 1000–1900 CE, compared to 0.36 in N-Scan). Moreover, C-Scan infers cooler temperatures than N-Scan during two longer periods roughly corresponding to the early half of MCA (900–1100 CE) and late half of LIA (1550–1900 CE). Also, the two records seem to be offset between 850 and 1300. However, it should be noted that the two reconstructions agree quite well on interannual timescale, except for the period 1230–1280. The more or less anti-phase behaviour in C-Scan between 1150 and 1250–11, we see that both records show a general cooling trend during the last millennium which is consistent with long-term astronomical forcing (Mann et al., 1999). However, the cooling is stronger in the large-scale reconstruction. This is likely due to the drop in sample sizes in C-Scan at that time. Comparing the 101-running R-bar in the two MXD series (after age-dependent spline detrending) of the two reconstructions shows that the mean running R-bar values are 0.45 and 0.46 for NH reconstruction being partly based on low-resolution paleo archives which have larger variance at millennium timescales (Moberg et al., 2005). Another reason could be that some of the paleo archives can also represent annual mean temperature evolution whose trend could be different with C-Scan (65 series (trees) covering 850–1406 (Cohen et al., 2012). C-Scan suggests a warm MCA peak between 1000–1100 CE) and N-Scan samples (50 series (trees) covering 850–1404, while the NH reconstruction suggests a longer warm peak between 950–1150 CE) respectively. This indicates that both reconstructions reflect common signals of their respective sample populations during the period of disagreement.

When compared with the 1500-long MXD-based May–August temperature reconstruction from Torneträsk (Melvin et al., 2013), C-Scan infers slightly warmer temperatures during 1200–1700 CE, and in general differs from the Torneträsk reconstruction at multi-decadal to century timescales during 1100–1900 CE. This could implicate that the warm maximum during MCA in central Scandinavia comes later than at some other places in the extra-tropical northern hemisphere, since the temperature

evolutions in different regions have shown differences in their timing and magnitude during MCA (PAGES 2k Consortium, 2013). However, they are in quite good agreement on interannual timescale. The running \bar{R} curves also indicate the both reconstructions reflect common signals of their respective sample population.

Despite the proximity, C-scan shows some different features from the temperature evolution in Northern Fennoscandia, such as a later onset of the LIA. This possibly indicates that the warm-season temperature evolution differs also within Fennoscandia. Under anthropogenic forcing conditions, global temperature shows a significant warming trend. However, the warming trends can be different in their magnitudes in different regions, due to differences in regional settings and processes. In addition to the different heat capacity between continent and ocean and the snow-ice feedback, other physical mechanisms behind this should be well addressed in order to project the future regional temperature. To well address this issue, more high-resolution regional temperature reconstructions are needed. Seasonal differences in temperature evolution, as mentioned above, could also be the reason of the discrepancy of the warm maximum between the two reconstructions. Both reconstructions show that the coldest multi-century periods occur during 1600–1900 CE. Moreover, the two reconstructions show less coherent variability during the period 950–1300 CE (corresponding to MCA). The temperature evolution difference during this period has been detected from many paleoclimate reconstructions from regional, continental to hemispheric scale (PAGES 2k Consortium, 2013; Masson-Delmotte et al., 2013). In order to make clear the temperature evolution during MCA, efforts should be made to increase the number of high-temporal resolution temperature reconstruction during this period. In another aspect, the reasons of the differences in regional temperature evolution should be also investigated from circulation perspectives.

4 Conclusions

An updated and extended version of the Jämtland MXD chronology was used to reconstruct the warm-season mean temperature (April–September) evolution in Central-central Fennoscandia for the period 850–2011 CE. Due to the fact that the samples come from different elevations, the new reconstruction, called C-Scan, was based on mean-adjusted data subsequently standardised with using the RSFi method. Our new reconstruction suggests a MCA during ca. 1009 to 1108 warm-peak during ca. 1000 CE to 1100 CE, followed by a transition period before the onset of the Little Ice Age proper in the mid-16th century. The cooling trend (-0.48 per 1000) during 1000–1900 is greater than that inferred from northern Fennoscandia (Esper et al., 2012). During the last 1200 years, the late 17th century to early 19th century was the coldest period in central Fennoscandia, and the warmest 100 years occurred during the most recent century in central Fennoscandia, and the coldest decades occurred around 1600 CE. The new reconstruction suggests lower temperature during the late MCA (ca. 1100–1220 CE) and higher temperature during the LIA (1610–1850 CE) than

the previous reconstruction (G11) from the region. Comparing C-Scan to two independent summer temperature reconstructions from northern Fennoscandia, regional differences in temperature evolution are notable before 1300 CE. The difference may reflect a true difference in temporal evolutions of summer temperature, which could be related to changes in the large-scale circulation affecting the region, or they could be caused by low sample replication.

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Table 1. Tree-ring sampling sites and summary statistics of the MXD data.

Sampling sites	Elev	TS	NS	MTA	AMXD	MS	AC1
Furuberg-1 <u>Furuberg-north</u>	650	873–1112	3	156	0.74	0.118	0.556
		1189–2005	104	168	0.69	0.122	0.571
Furuberg-2 <u>Furuberg-south</u> (G11)	650	1497–2008	35	193	0.64	0.133	0.457
Häckervalen-top <u>ckervalen-south</u>	750	783–1265	30	130	0.66	0.125	0.415
		1276–1520	24	113	0.60	0.134	0.449
Häckervalen <u>ckervalen-north</u>	650	1778–2011	5	213	0.71	0.165	0.314
Lilla-Rörtjärnen*	560	952–1182	13	90	0.67	0.122	0.572
		1290–1668	9	147	0.63	0.122	0.655
		1750–1861	1	112	–	–	–
Öster Helgtjärnen*	646	929–1093	6	121	0.62	0.124	0.715
		1119–1333	3	104	0.72	0.122	0.625
		1336–1402	1	67	–	–	–
		1446–1568	2	110	0.76	0.106	0.676
Jens Perstjärnen*	700	1196–1382	2	153	0.62	0.133	0.753
Historical buildings	< 500	1107–1291	15	158	0.84	0.082	0.676
(Jämtland, Sweden)		1316–1827	118	161	0.79	0.089	0.576

Elev: source elevation (m a.s.l.); TS: time span (CE); NS: number of samples; MTA: mean tree age (year); AMXD: average MXD (g cm^{-3}); MS: mean sensitivity; AC1: first-order autocorrelation; * means that the sampling site is a lake. Some of the “mean tree ages” are less than 100 years, because the MXD measurement is only a part of a tree-ring width measurement which is much longer. The cutting of the samples is due to that some parts of the samples were too rotten for MXD to be measured. Tree-ring data from Furuberg-north, Häckervalen-south, Häckervalen-north, Lilla-Rörtjen, Öster Helgtjärnen and Jens Perstjärnen are newly added data. Tree-ring data from historical buildings are downloaded from International Tree-Ring Data Bank (ITRDB), which has been used in the previous tree-ring MXD based warm-season temperature reconstruction (the G11). In this paper, the historical building data was used in the analysis, but was not used for the new temperature reconstruction, while tree-ring data from other sites were used in the new reconstruction.

Table 2. Calibration and verification statistics of the warm-season temperature reconstruction.

MXD RSFi chronology			
Calibration period	1890–1950	1951–2011	1890–2011
Correlation, R	0.82 ^a	0.67 ^a	0.77 ^a
Explained variance, R^2	0.67	0.46	0.59
No. of observations	61	61	122
Verification period	1951–2011	1890–1950	–
Explained variance, R^2	0.46	0.67	–
RE ^b	0.55	0.71	–
CE ^b	0.44	0.65	–

^a the correlation is significant at $p < 0.01$ significance level; ^b RE means reduction of error; CE means coefficient of efficiency.

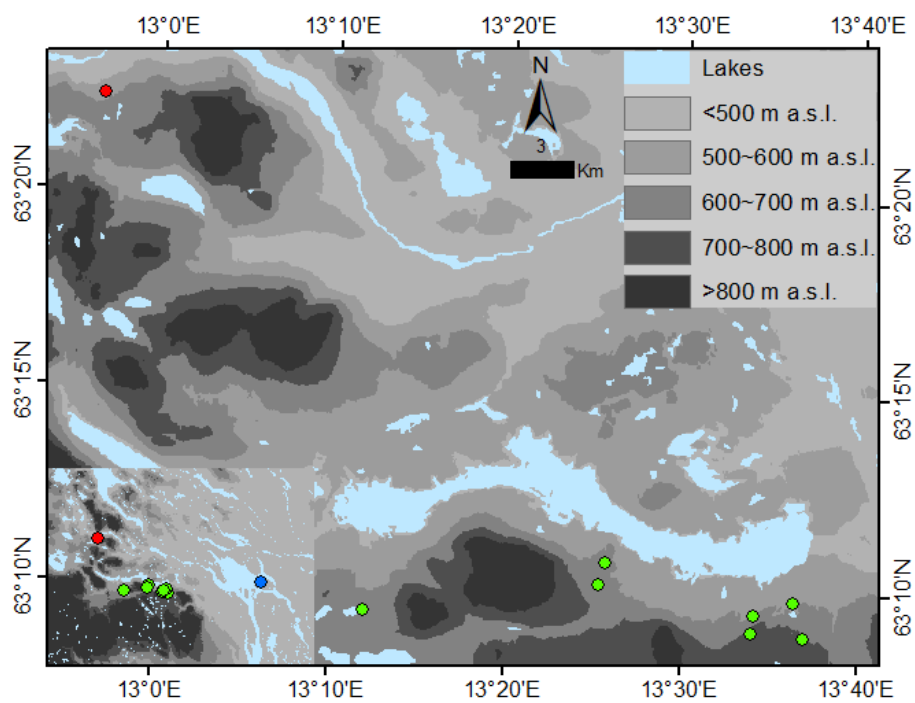


Figure 1. Map showing the locations of tree-ring sampling sites (green dots), except for historical samples, and Duved (red dot) and Östersund (blue dot) meteorological station.

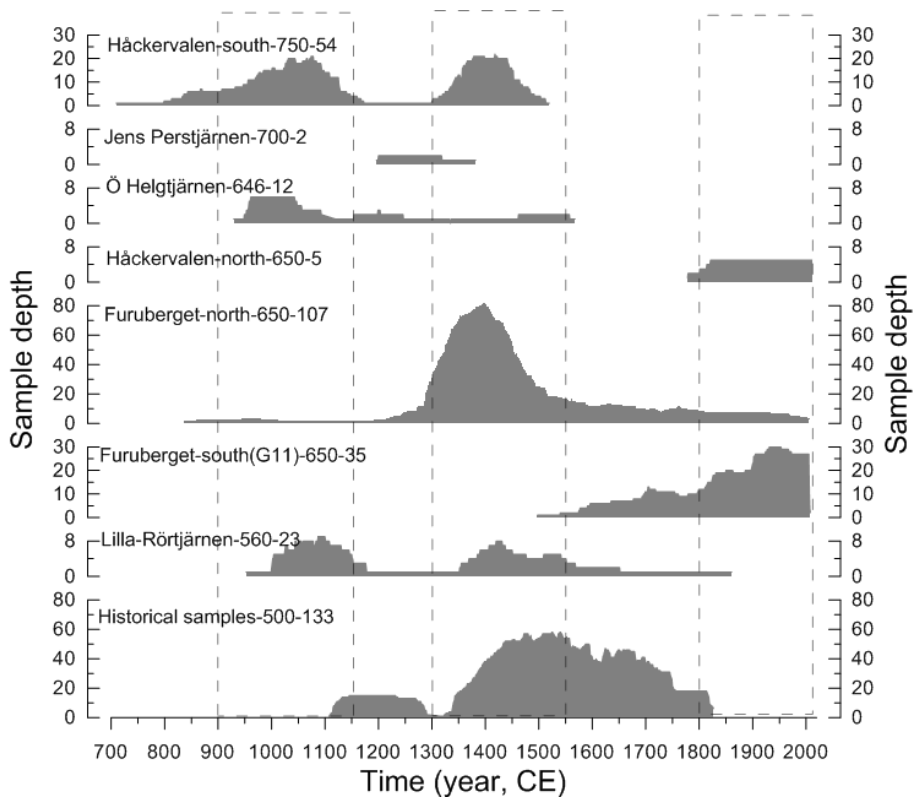


Figure 2. Sample replication and time span in each site/group. The site/group names, elevations and the number of samples were given on the upper left corner of each subplot. Dashed line frames mark three common periods with most of the samples.

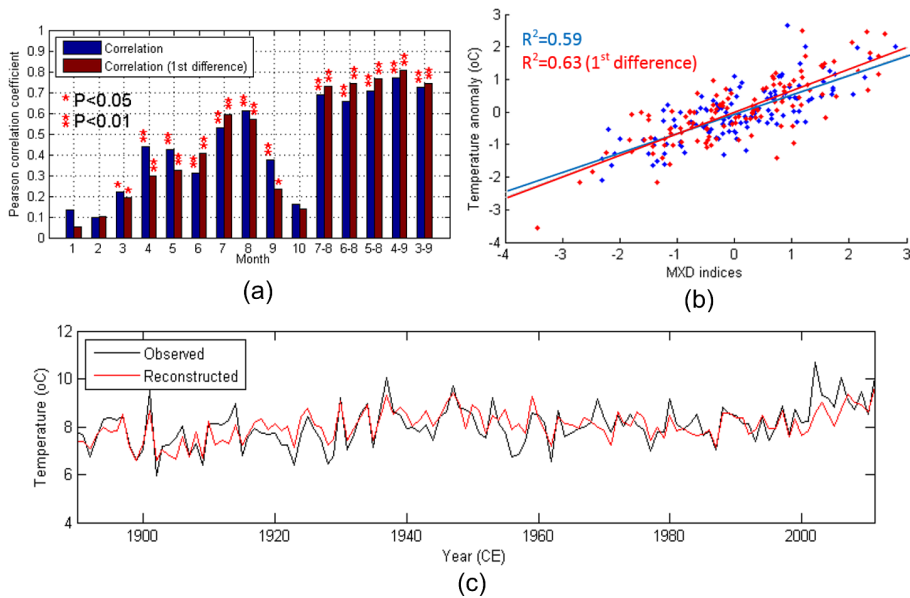


Figure 3. (a) Correlation between the mean-adjusted MXD data, standardised with RSFi method, and monthly mean temperature over the period 1890–2011 CE. Correlations are given from January to October of the growth year and July–August, June–August, May–August April–September (warm season) and March–September average; (b) Linear relationship between MXD data and warm-season temperature (anomaly relative to 1961–1990 mean (blue) and 1st difference (red)); (c) comparison of reconstructed warm-season temperature (red) with observed Duved warm-season temperature (black) for the period 1890–2011 CE.

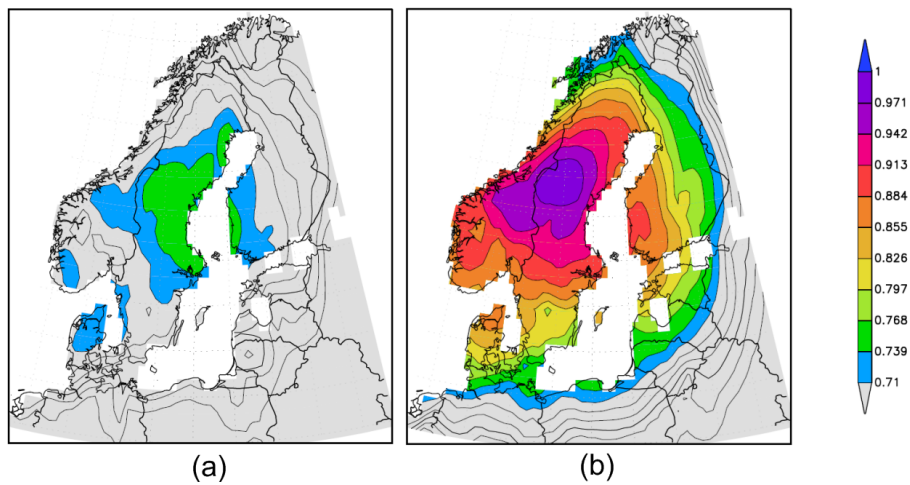


Figure 4. Field correlations of the reconstructed warm-season temperature from (a) the new chronology in this study and (b) observed Duved warm-season temperature with the gridded warm-season temperature from CRU TS3.22 $0.5^\circ \times 0.5^\circ$ dataset during the period 1901–2011 CE. Grey areas outside the $r = 0.71$ isoline represent the correlations at $p < 0.001$ significance level. The field correlation maps were plotted using the “KNMI climate explorer” (Royal Netherlands meteorological Institute; <http://climexp.knmi.nl>; Van Oldenborgh et al., 2009).

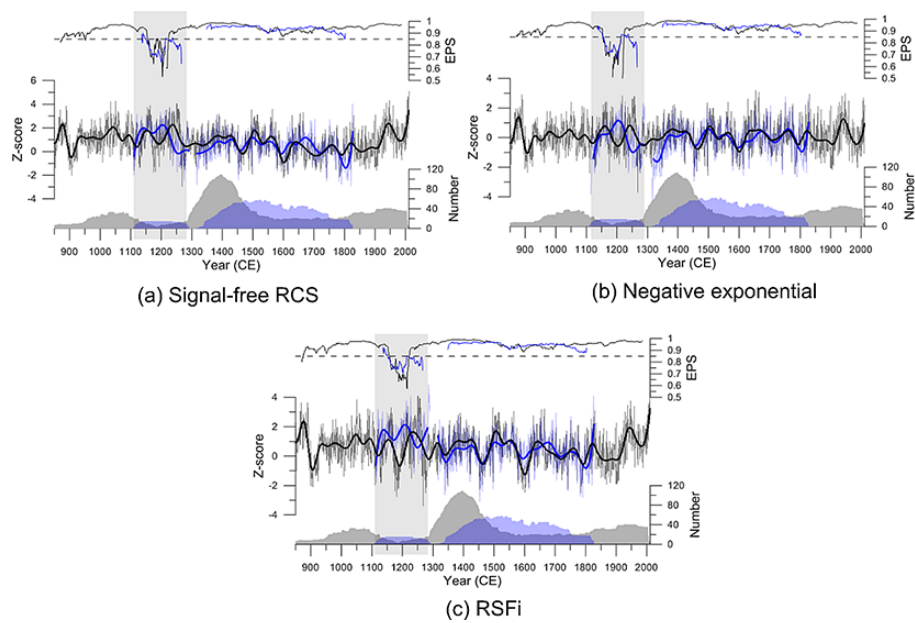


Figure 5. Comparison of the z scored (based on 1700–1800 CE) interannual (thin curves in the middle subplot) and multi-decadal-multidecadal (50 year spline) (bold curves in the middle subplot) variability of the historical (blue) and “in-situ” sample based (black) chronologies after (a) signal-free RCS standardisation (smoothed by age-dependent spline), (b) negative exponential curve standardisation and (c) RSFi standardisation. Sample replication and EPS information was given in the lower and upper subplot. The low EPS time period around 12th century was marked by dark with a shaded background.

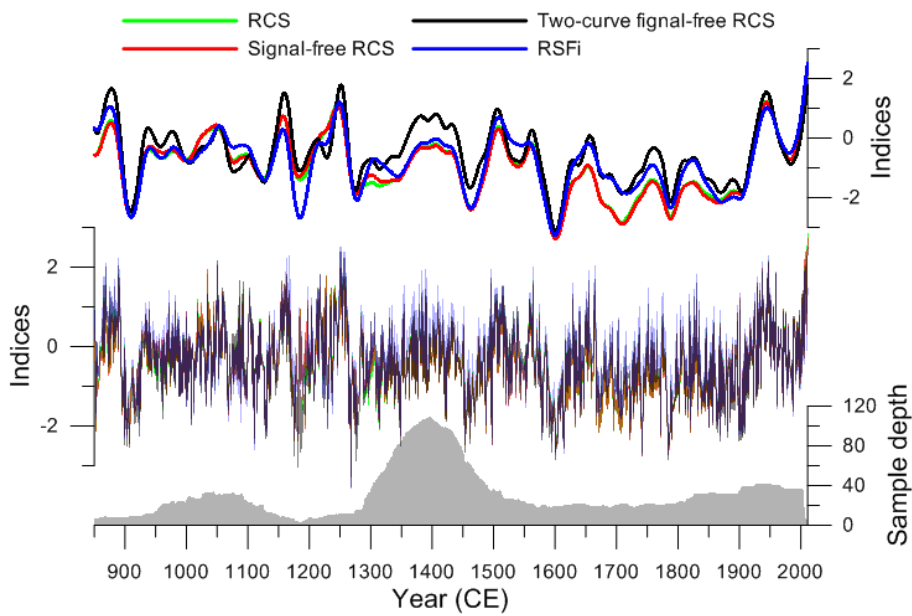


Figure 6. Comparison of the interannual (thin curves in the middle subplot) and ~~multi-decadal~~ multidecadal (50 year spline) (bold curves in the upper subplot) variability in the mean-adjusted 238 field-sample based chronologies based on RCS standardisation (smoothed by hegershoff function) (green curves), one-curve signal-free RCS standardisation (smoothed by age-dependent spline)(red curves), two-curve signal-free RCS standardisation (smoothed by age-dependent spline) (black curves) and RSFi standardisation (black-blue curves). Sample replication was given in the lower subplot.

(a) Correlation between the mean-adjusted MXD data, standardised with RSFi method, and monthly mean temperature over the period of 1890–2011 CE. Correlations are given from January to October of the growth year and July–August, June–August, May–August April–September (warm season) and March–September average; (b) Linear relationship between MXD data and warm-season temperature (anomaly relative to 1961–1990 mean (blue) and 1st difference (red)); (c) comparison of reconstructed warm-season temperature (red) with observed Duved warm-season temperature (black) for the period of 1890–2011 CE. Field correlations of the reconstructed warm-season temperature from (a) the new chronology in this study and (b) observed Duved warm-season temperature with the gridded warm-season temperature from CRU-TS3.22 0.5×0.5 dataset during the period of 1901–2011 CE. Grey areas outside the $r = 0.71$ isoline represent the correlations at $p < 0.001$ significance level. Color bars represent the magnitude of the correlations.

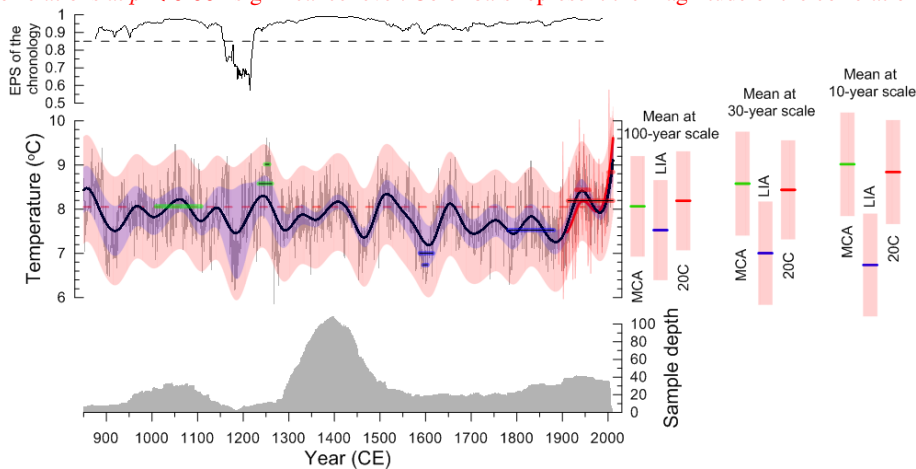


Figure 7. Annual (gray grey) and 80 year spline filtered (bold black) warm-season temperature variability over the period of 850–2011 CE inferred from the new chronology in this study. Purple and pink shading indicate the chronology uncertainty and the total uncertainty of the reconstruction (including chronology uncertainty and reconstruction uncertainty), as expressed as the $2 \times$ the standard error in their upper and lower limitations. The gray grey shading and the thin black curve indicate the sample depth and EPS values (with the dashed line show the threshold of 0.85) of the chronology. Observed annual and 80 year spline filtered warm-season temperature is shown by the thin red curve and the bold curve, with the red dashed line indicating the 1961–1990 mean. The short lines in the right part of the panel mark the mean temperature levels of the warmest 100, 30 and 10 years in MCA (10th–13th century, [Grove and Switsur, 1994](#) ([Grove and Switsur, 1994](#))) (green) and 20th century (red), and the coldest 100, 30 and 10 years in the LIA (14th–19th century, [Grove, 2001](#) ([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.

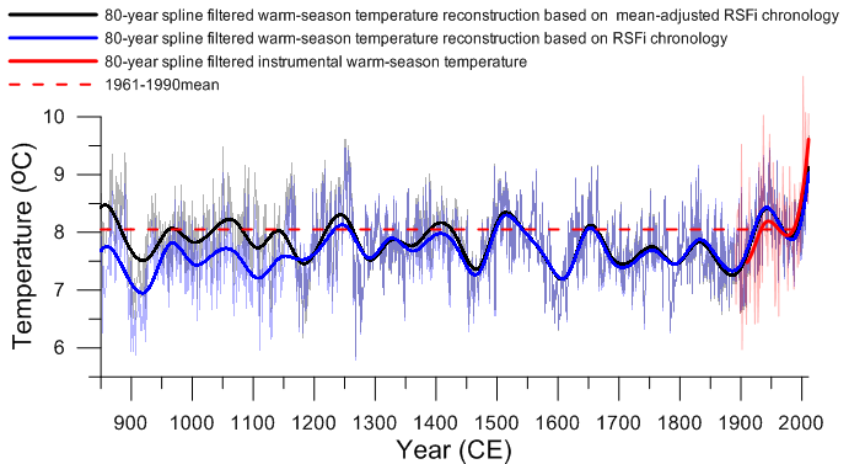


Figure 8. Comparison of the reconstructed warm-season temperature based on the mean-adjusted MXD samples (black) and the unadjusted MXD samples (blue). Red curves show the observed warm-season temperature variability. Light curves indicate the interannual variability, and the bold curves show the variability smoothed by 80 year spline filter. Dash-Dashed line shows the observed 1961–1990 mean warm-season temperature.

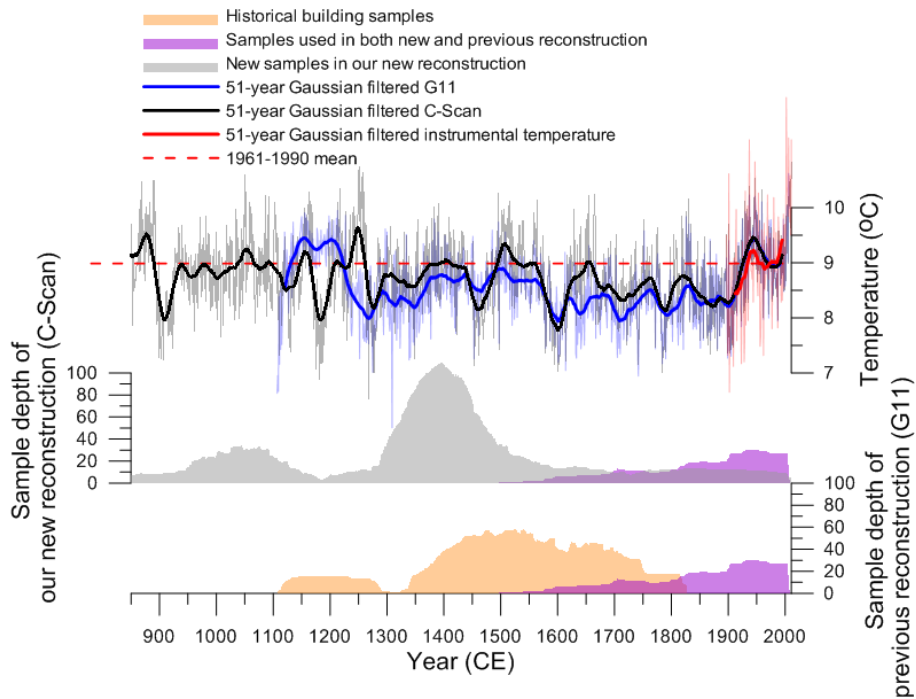


Figure 9. Comparison of annual variation of the z-scored (based on 1890-2006) C-Scan (thin black-grey curve) with (a) N-Scan (Esper et al., 2012) the previous tree-ring MXD based central Scandinavia warm-season temperature reconstruction (thin blue curve), and (b) Torneträsk (Melvin et al., 2013) reconstruction (thin blue curve Gunnarson et al., 2011). Bold black and blue curves show the variability after 80 spline 51-year Gaussian filtering. The sample depths (Number-number of trees) of the two chronologies-reconstructions are marked by the black and purple (C-Scan) and blue-orange and purple (N-Scan/G11) shadings. The green/orange line indicates 101 running r-bar of C-Scan red curves indicate the observational temperature variability and N-Scan chronologies its 51-year Gaussian filtered variability. The dashed line is marked as 0 level red curve marks the observed 1961-1990 mean temperature. N-Scan data is downloaded from National Climatic Data Center, US National Oceanic and Atmospheric Administration (NOAA,) (ONLINE RESOURCE:).

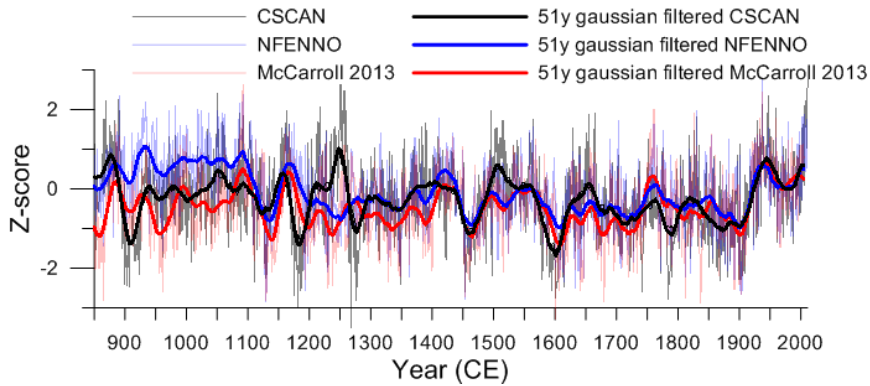


Figure 10. Comparison between C-Scan (black) with tree-ring MXD based northern Fennoscandia (NFENNO) summer temperature reconstruction (blue) (Matskovsky and Helama , 2014) and multi-proxy based northern Fennoscandia summer temperature reconstruction (red) (McCarroll et al., 2013). Bold curves show the variability after 51-year Gaussian filtering. z scores were calculated based on 1890–2005 CE.

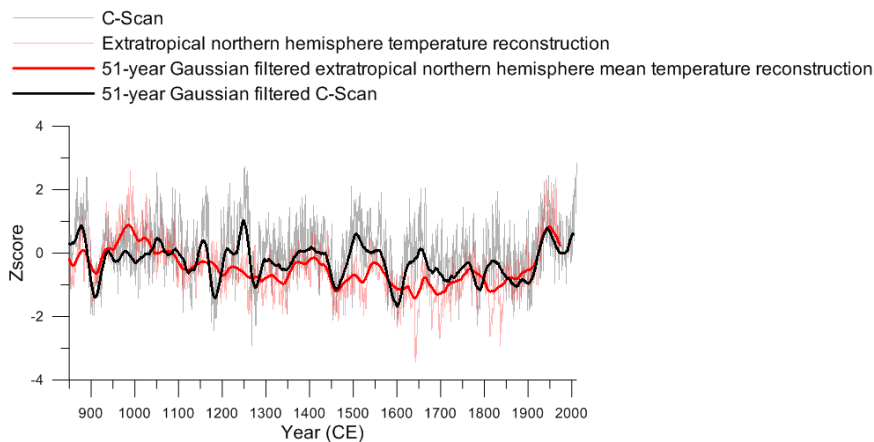


Figure 11. Comparison between C-Scan (thin grey curve) and the extratropical northern hemisphere multi-proxy annual mean temperature reconstruction (thin red curve, Christiansen and Ljungqvist , 2012) during 851–1973 CE. Bold black and red curves show the variability after 51-year Gaussian filtering. z scores were calculated based on 1850–1973 CE.

Dear Editor,

The manuscript (No.: cp-2015-4) entitled ‘1200 years of warm-season temperature variability in central Fennoscandia inferred from tree-ring density’ has been revised according to the reviewers comments.

We are very thankful for the constructive and insightful comments from the reviewers. All comments have been considered when revising the manuscript. Below all responses (in **bold font**) to the comments are listed.

Response to reviewer #1

1. It is unclear which part of the MXD data is new, which portion of the MXD data used in this paper originates is actually the same as G11 data (the abbreviation the authors use) or data produced and analysed previously. The authors are recommended to provide this information.

Responses: This has now been clarified in Table 1. Tree-ring data from ‘Furuberget-south’ is the data that has been used in both of the previous (the G11) and the new (C-Scan) reconstruction. Tree-ring data from Furuberget-north, Håckervalen-south and Håckervalen-north are the newly collected and measured data. Tree-ring data from Lilla-Rörtjärnen, Öster Helgtjärnen and Jens Perstjärnen are the data collected some years ago, and measured recently. (Changes: see notes in Table 1, page 22)

2. It should be mentioned explicitly already in the abstract, how this paper advances the research in the region of central Fennoscandia and Sweden by introducing new data, what are the new insights produced by this paper in comparison to G11 study and Linderholm et al. (2014a), and the other past MXD studies in this region (also the new MXD papers from Lapland incl. Esper et al. (2014), Pritzkow et al. (2014) and Matskovsky and Helama 2014) are studies to be introduced here), what are the advancements produced in this paper in comparison to G11 w.r.t. the MXD data, the standardisation and reconstruction methods, how is the reconstruction produced in this paper advancing the science w.r.t. G11 paper. Without this information the reader of the paper is confused and the value of the current paper is questioned.

Responses: We have revised the abstract and introduction. We briefly review the state of dendrochronology, MXD length and spatial coverage, and MCA to identify some areas for improvement. We finally state what we intend to do to contribute. (Changes: see abstract and introduction, page 1, line 1 – page 4, line 106)

The main advance of this paper is to extend G11 back to 850 CE (covering the important and spatially variable MCA (cf. PAGES2K consortium)), with new collected MXD data. And to replace the questionable historical material which made out a large part of the G11 reconstruction. This has improved our knowledge about the >millennium summer

temperature evolution and perhaps unfortunately made it even more elusive, which further highlights the need for even more material covering a larger part of the region from more sites to really come to terms with the MCA in Fennoscandia. (Changes: see page 3, line 93 – page 4, line 106)

Compared with the G11 reconstruction, the new reconstruction (C-Scan) suggests that the warming between 1120 and 1220 detected by G11 reconstruction is not that distinguished. Compared with the reconstructions from northern Fennoscandia (i.e. Matskovsky and Helama, 2014 and McCarroll et al., 2013), we did see the spatial differences in temperature evolution in northern and central Scandinavia. We summarized this information, and gave them in the abstract in the revised version of the manuscript. For standardization method, we used regional curve adjusted individual signal-free approach (RSFi) to standardise the MXD series. This method has a better potential to remove unwanted noise (e.g. related to stand dynamics) on tree level comparing to other RCS standardisation methods. (Changes: see section 3.2, page 9, line 295 – page 10, line 316 and section 3.5 and 3.6, page 12, line 390 – page 14, line 450)

3. Second major source of criticism: the methods used in this paper are not sufficiently described. In page 6, the authors refer to G11 paper w.r.t. setting of ITRAX method. And they also refer to standard techniques (line 16-17). It is hard to believe there is such a thing as standard method.

Responses: We added detailed information about the settings of ITRAX method and the sample preparation processes in the revised manuscript. (Changes: see page 5, line 146 -- line 162)

4. If any adjustments were made, in G11 paper or in this paper, to modify the MXD data from Walesch (the authors spell this differently in lines 15 and 16) and ITRAX techniques, this should be mentioned if it was done in G11 paper or by the authors of this paper.

Responses: In G11 paper, the authors did not adjust mean level and variance of raw MXD data before standardisation. In our paper, we adjusted the mean level of raw MXD data, no matter if data were measured by Walesch or ITRAX techniques. We gave more information about this in the revised manuscript. We have corrected the spelling. (Changes: see page 5, line 163 – page 6, line 194 and page 5, line 161)

5. It is interesting to find out that the authors are also adjusting (page 6, lines 18 onwards) the absolute MXD values as dictated by temperature lapse rate using a method which they have developed previously in yet unpublished paper (Zhang et al. 2015). As this paper is not yet published, it is not possible to judge if this method is reasonable at any level and what are the requirements and actual statistical procedures to attain this adjustment. It is recommended that if this paper is not yet published, the authors make an illustration of the method in the supplementary portion of the paper. If not done so, the current paper is

done using fully unpublished methods and this is not following any scientific requirement. This is important because the adjustments of this type can introduce low-frequency variability to the reconstructed temperature data.

Responses: That paper (Zhang et al. 2015) has been published (DOI: 10.1007/s00468-015-1205-4), and can be found on line. (Changes: see page 5, line 164, page 6, line 180 and line 182)

6. The authors should also include all the statistical tests and their verbal illustration in the methods section. Now there are statistical measures and tests done to the data (Table 1 and 2) which are not described in the correct section of the text.

Responses: We have included all the statistical tests and their description in the methods section in the revised manuscript. (Changes: see section 2.5 and 2.6, page 8, line 246 – page 9, line 274)

7. It is also suggested that the language of the paper is reviewed by native English speaker. At this point, there are several inconsistencies in the text needing clarification.

Responses: Done.

8. Smaller points of criticism: p2, l6, it is unclear what “mean adjusted” actually means

Responses: Now clarified. (Changes: see page 1, line 7—8)

9. p2, l7, RSFi is mentioned as a method with no other information what this actually means and stands for

Responses: Now clarified. (Changes: see page 1, line 9 – 12)

10. p3, l15, once again the author mention something new, Delta-Density, but this is not described

Responses: Now removed. (Changes: see page 2, line 51)

11. p3, l20, dry deadwood is also subfossil wood

Responses: The name of subfossil wood has been used in many of our studies to describe the wood which has been buried in the lake sediments for hundreds or thousands of years. Dry deadwood cannot be seen as subfossil wood since it is not buried in sediments. We have explained the meaning of subfossil wood in the revised manuscript. (Changes: see page 2, line 59 – 60)

12. p3, l21, for the language, it would be good to decide if G11 means the study or the data used in the study

Responses: G11 means the previous reconstruction. This is clarified in the introduction of the revised manuscript. (Changes: see page 2, line 44 – 45)

13. p4, l2, what is this study, what did it do, and how it relates to your study

Responses: This is an analysis in G11 paper by visually comparing the temperature reconstructions by Gunnarson et al. (2011) and by Gouirand et al. (2008), which shows the spatial differences in regional temperature evolution. We added this information to emphasize the importance of producing a new temperature reconstruction in central Fennoscandia. However, we removed this in the revised manuscript. (Changes: see page 3, line 71 – 78)

14. p4, l13, it is uncertain what is the uncertainty that the authors mention here

Responses: The ‘uncertain’ mentioned here is related to the uncertainty caused by the possible weak summer temperature signals in the historical samples. This is clarified in the revised manuscript. (Changes: see page 3, line 69 – 79)

15. p5, l3-12, the authors are recommended to add papers that actually show the influence of all these factors to the study region

Responses: Done. (Changes: see page 4, line 113 – 118)

16. p7, l24-27, really unclear sentence

Responses: This sentence has been rewritten. (Changes: page 7, line 210 – line 213)

17. p8, l14 onwards, when using RCS methods, do the authors always apply the RCS method using a single or multiple curves. It is surprising to that the author skip the papers of Melvin & Briffa (2014, 2014b) “CRUST: Software for the implementation of regional chronology standardisation: part 1. Signal-free RCS” and “CRUST: Software for the implementation of Regional Chronology Standardisation: Part 2. Further RCS options and recommendations”, where the M & B demonstrate the importance of using multiple curves in RCS.

Responses: We used single RCS curves in the standardisation. For example, in Figure 4, the chronologies in green and red colour are both based on single RCS curves. The RSFi chronology is not based on single curve. We have added a comparison with the multiple-curve-based RCS chronology in the revised manuscript. (Changes: see page 9, line 296 – page 10, line 316 and Figure 6, page 27)

Response to reviewer #2

1. Be careful with generalised, unquantified, comments “an improved” chronology? Improved by what metrics? Such qualifying comments need to be evidence based.

Responses: The previous reconstruction, G11, is largely based on the tree-ring samples collected from historical buildings, especially for the period before 1500 CE. The geographic source of these samples is unclear, thus the climatic signal that the samples reflects is more uncertain than tree rings collected at the tree line. In this study, new samples collected from tree-line area were used to replace the historical samples. We think that this as an improvement compared to the previous study. Furthermore, the chronology is extended by some 300 years back in time. We will more clearly phrase that this is what we mean in the revised manuscript. **(Changes: see page 3, line 93 – page 4, line 106)**

2. Improved and clarified aims and objectives and citing of the work in the broader context of northern Fennoscandian dendroclimatology

Responses: We have revised the introduction to clarify the aims and objectives. In order to put our study in a broader context, we compared our new reconstruction with the tree-ring MXD based summer temperature reconstruction from northern Fennoscandia covering the MCA (Matskovsky and Helama, 2014) and the multi-proxy based northern Fennoscandian summer temperature reconstruction (McCarroll et al., 2013) **(Changes: see introduction, page 2, line 30 – page 4, line 106, section 3.6, page 13, line 412 – page 14, line 450 and Figure 10, page 31)**

3. Improved details on the physical and statistical methodologies used.

Responses: In the revised manuscript, we have now added detailed information about tree-ring sample preparation and MXD measurements. The Zhang et al. (2015) is now published, but we anyway added a brief summary of the findings in that paper about the mean adjustment method. **(Changes: see page 5, line 146 – page 6, line 194)**

4. Improved and more detailed discussion of the results and their relevance to the wider climate evolution of the region over the last millennium

Responses: The discussions now include more info about the similarity of the temperature evolution between northern and central Fennoscandia focusing on MCA. The possible causes are also illustrated. **(Changes: see section 3.6, page 13, line 412 – page 14, line 450)**

5. Improved clarity, language and grammar.

Responses: We have now improved the clarity, grammar and language.

6. “C-scan suggests a later onset of LIA and a larger cooling trend during 1000–1900 CE than previous MXD based reconstructions” Again this is difficult to qualify as comparisons are not made with a wide range of reconstructions.

Responses: We have now added more reconstructions that included MXD and compare to them. We still remove this statement in the revised manuscript. (Changes: see section 3.6 and 3.7, page 13, line 412 – page 15, line 503 and page 1, line 23 – line 25)

7. The motivation for the sampling strategy could be more clearly explained and linked to a clearer indication of what is new material and which parts of the chronology are preexisting? I am confused on the provenance of the majority of the wood. You indicate that most of the trees are of known (temperature sensitive) provenances, however also that a lot of building materials were used? This should be clarified and expounded upon.

Responses: As mentioned in point 1, we intended to use the new collected samples to replace the samples collected from historical buildings. In addition to the samples from Furuberget-south (used in the G11), all the samples from other sites (except for historical buildings) are new material. The building materials were used in the comparison, but not used in the final chronology and reconstruction. This information will be clarified in the notes of Table 1. The new Figure 9 also clearly gives information about the provenance of the samples. (Changes: see Table 1, page 22 and Figure 9, page 30)

8. At the end of the introduction the motivation for the study, its aims and objectives, relevant background remains murky at best. I would recommend some clear aims and objectives, linked to gaps in knowledge, which this data set can address and perhaps tied to some hypotheses which can be tested with this new data? This is particularly important in such a densely studied part of the world.

Responses: We have reworked and hopefully improved the introduction. (Changes: see introduction, page 2, line 30 – page 4, line 106)

9. It's ok to refer to another paper for the details of a method but some methodological elements should be included to give the reader an indication of sample preparation and protocols etc.

Responses: We have now added information about the method of sample preparation and MXD data measurement in the revised manuscript. (Changes: see page 5, line 146 – line 162)

10. Further discussion, detail and discussion of the implications of the mean adjustment procedure are also required.

Responses: We discussed mean adjustment procedure more in the revised manuscript. However, more detailed information can be found from Zhang et al. (2015). That paper is now published. (Changes: see page 5, line 163 – page 6, line 194)

11. Grammar, language and clarity really need addressing in the methods section.

Responses: We have now corrected the grammar and language in the methods section. (Changes: see method section, page 6, line 196 – page 7, line 234)

12. Detrending methods – the section is a little outdated. There is a huge body of literature now on differences in standardisation methods, signal preservation and the impacts of different detrending methods on variance preservation. I would recommend reading more widely on these topics and extending this discussion.

Responses: We added the latest relevant literatures about the standardisation methods in the method section. A new comparison and new discussions were added in the discussion section. (Changes: see page 7, line 214, section 3.2, page 9, line 296 – page 10, line 316 and Figure 6, page 27)

13. Results are broadly thoroughly discussed however I find the conclusions too brief. What are the broader climatological features of interest in the series? What does the evolution reveal in comparison to ideas about known climate transitions in the region over that time period? What climatic features might explain differences between this southern reconstruction and more northerly one?

Responses: We have added more contents in the conclusion. E.g. the results of the regional temperature comparison and the possible causes of the differences in regional temperature evolution. (Changes: see conclusion, page 15, line 505 – page 16, line 521)

14. As the authors note they do present a comparison with Matskovsky and Helama, 2014 which, critically make reference to the new Toneträsk series. Comparisons are important, as the commentator points out, and various other options are available – McCarroll et al 2013 is a robust other option for comparisons (from a more northerly site) and contains useful discussions on variance differences which may be relevant

Responses: We have added the comparison with the MXD based northern Fennoscandia summer temperature reconstructions (Matskovsky and Helama, 2014; McCarroll et al., 2013), and discuss the results. (Changes: see section 3.6, page 13, line 412 – page 14, line 450)

Hopefully we have addressed all of their concerns. In addition to the changes made in response to the reviewers' comments, we also made some language corrections in the manuscript to facilitate the reading and interpretation of the same.

Best regards,

Peng Zhang and co-authors