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 substantially revised (Please see the marked-up version below).

The revision is based on the last revised manuscript. We thank the two reviewers for their constructive and insightful comments. All comments have been considered when revising the manuscript. The point-to-point responses to the comments are listed below.

<u>*Response to reviewer #2*</u>

1. Non-addressed point 1: "I feel more insight could be gained as to the significance of the new reconstruction with broader comparisons with existing studies and the already widely described palaeoclimatic evolution of the region"

Re: We have now extended the comparisons to all other published millennium-long annually-resolved temperature reconstructions in the whole of Fennoscandia. We have now also summarized the characteristics of the warm-season temperature evolution of the past millennium in this region and made suggestions concerning their possible forcing. See section 3.3.

2. Grammar and clarity. Unfortunately there are still numerous examples of poor grammar and clarity of language which need addressing (e.g Abstract lines 4-5. Too many uses of 'used', Abstract line 10 – plurals not correct. Abstract line 15 – plurals not correct (temperature/temperatures)).

Re: We went through the revised text carefully and corrected the errors.

3. I do not feel that the request to provide clearer (identifiable, bullet points maybe) aims/objectives or testable hypotheses have been met. This omission makes it hard for the reader to see the motivation for the study and to tie concluding points to objectives.

Re: Aims and objectives have now been revised, according to the suggestion of the reviewer. Now the aim reads 1) extend G11 back in time, covering also the MCA, and 2) as far as possible, replace the historical samples with samples collected from past and present tree-line environments where the provenance was known. Using this new reconstruction, we re-examined the warm-season temperature evolution in central Scandinavia during the last 1150 years, and compared it to other reconstructions from northern Scandinavia and southern Finland. This improved dataset allows us to provide new insight into temperature variability during the last millennium in central Scandinavia.

<u>*Response to reviewer #3*</u>

1. The reconstruction technique, for example, is not described at all, neither in the method section nor elsewhere, although this is an essential information to replicate the study. There are also more details required regarding the detrending (see below) and the error estimates. The latter is only very briefly addressed in the figure captions.

Re: The reconstruction technique and the estimation errors are now more thoroughly described and can be found in section 2.5.

2. I wonder why the authors used negative exponential functions to approximate the raw MXD data. Usually a so called Hugershoff function fits much better for MXD data. This might not affect the overall trends of the RSFi-chronology but low replicated periods with a low mean tree age (like the early MCA) might be altered.

Re: The tree-ring series are now only standardized with two-curve Signal-free RCS and the RSFi method, using age-dependent spline curve fits to each individual measurement. This information is now clarified in the last paragraph of section 2.3.

3. Although I do see the benefit and the need of adjusting the mean of different tree-ring sites, there are two major points of criticism w.r.t. this method: (1) The information given is again not sufficient to replicate the study! Even the paper cited (Zhang et al. 2015) is not elucidating since it only uses a subset of the proxy data. For example, it remains unclear how sites that do not cover the (whole) 1300-1550 period were treated. It would also be desirable to find the actual values that were added/subtracted for each site somewhere in the manuscript/supplement. In consideration of other potential biases (see (2)) this would yield an estimate for the size of the effect.

Re: This point is now addressed in the last paragraph of section 2.2. The actual values that were added to all the samples at each site is presented in Table 1.

4. (2) Additionally, it seems very important to report the mean age of the samples in the window of overlap. Basically the fact that dendrochronologists detrend their samples w.r.t. age stems from the assumption that the mean value differs significantly with age. Hence, a homogeneous age distribution is an ultimate prerequisite for applying such a "mean-adjustment". This needs to be stated clearly and proven(!) in some way. Otherwise, the detected long-term cooling in the adjusted chronology could well be perceived as a remnant of age-trends. In order to validate the applied methodology I strongly recommend displaying age-aligned Regional Curves for samples in the common period (1300-1550) before and after mean-adjustment in a supplementary figure.

Re: We agree with the point that if we adjusted the mean value of the elder part (old age of a tree) of the samples to have the same mean with the younger part of some other samples, then this will bring bias. We have stated the importance of a homogeneous age distribution in the reference period for the mean-adjustment method in section 2.2, and we have shown the time span of the adjusted samples and reference samples in the supplementary. To validate the applied methodology, we also added a figure in the supplementary showing the age-aligned regional curves for the samples in the reference period before and after mean-adjustment and compared them with the age-aligned regional curve of the reference samples from Furuberget-north.

5. Grammar and language still need improvement, especially in the revised sections.

Re: We went through the revised text carefully and corrected the errors.

6. The revised manuscript puts much weight on the comparison with other reconstructions (instead of refining the methods section). For a fair judgement, however, some additional issues should be considered: (1) Error-estimates should be displayed, at least for the new reconstruction, to identify really significant differences.

Re: Done.

7. (2) Temperature-anomalies should be compared to temperature-anomalies. There's no obvious need to use z-scores.

Re: Fig. 8 has been changed for temperature-anomalies comparison.

8. (3) For the large-scale comparison, the NH reconstruction by Christiansen and Ljungqvist (2012) is not the ideal choice. In the IPCC ensemble of reconstructions this is the one that clearly sticks out due to its high low frequency variability. And as already stated by the authors, the seasonal window differs.

Re: In the revised manuscript, the comparison with the hemispheric-scale reconstruction has been removed, and we only examined the comparisons with other regional temperature reconstructions in Fennoscandia.

9. It's a pity that most samples terminate in 2006/7. Only 5 samples extend to 2011. Generally the interest in the most recent years of climate reconstructions is fairly high. Especially for tree-ring studies, which can be affected by the so called 'divergence problem'. AN update based on old samples will be outdated soon.

Re: Yes, we agree, but we have no means of taking care of this shortcoming at this point.

10. I didn't find a statement about data availability in the end of the main text. All data used in this study should be made available.

Re: 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. A statement about this is now provided in the supplementary.

11. Lines 89 and 104: Replace 'glacifluvial' with 'glaciofluvial'.

Re: Replaced.

12. Line 58-67: Is the MCA really the key target of this story? There's eventually not much light brought into this period.

Re: We have changed this statement. MCA is an important time period. Thus the goal of this paper is to extend G11 to cover the whole MCA with as many samples as possible, based on collected data from present or previous tree-line areas. A critical discussion about MCA has been added to the second paragraph of Section 3.2.

13. Line 124: Remove dot in '(Table. 1)'.

Re: Removed.

14. Line 126-128: Sentence unclear. It implies that the authors know what the temperature difference between MCA and LIA was, which I doubt. Rewrite.

Re: This sentence has been removed.

15. Line 143 and 152: 'subtracted from or divided by' - this is not termed correctly. Should be a-b and a/b, not a-b and b/a. Reword.

Re: Reworded.

16. Line 166: Add information about the exact settings for the detrending (like: negative exponential functions used for the individual fitting, ratios or residuals between fitted function and raw data,…).

Re: Added.

17. Line 173: In the figures, EPS-values don't seem to have a 25-year period of overlap.

Re: Yes, you are right. We have corrected this typo.

18. Line 237: Replace 'multidecadal' with 'multicentennial'.

Re: Corrected.

19. Line 238: Be more consistent with using either the term multi- or two-curve RCS.

Re: The 'multicurve' expression is replaced by 'two-curve'.

20. Line 269: '20th century'?

Re: Corrected.

21. Line 321-322: In which frequency domain?

Re: Multidecadal, but this part of discussion has been rewritten.

22. Figure 1: It's hard to locate the map section within Scandinavia. References (borders, towns,…) missing.

Re: There are no borders in the Fig. 1b. The figure has been redraw. A lake's and some towns' names have been added. We also added another map (Fig. 1a) to show the general locations of the sampling sites within Scandinavia.

23. Figure 4: The sampling site should be marked.

Re: Marked.

24. Figure 6: Correct spelling in the legend.

Re: Corrected.

We believe that we have appropriately addressed all the reviewers' concerns in the revised manuscript. **The language has also be improved. One such example is that we changed the title of the manuscript to '1200 years of warm-season temperature variability in central Scandinavia inferred from tree-ring density'.**

Sincerely,

Peng Zhang on behalf of all co-authors

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

Peng Zhang[1], Hans W. Linderholm[1], Björn E. Gunnarson[2], Jesper ~~Björklund[1]~~Björklund[3], Deliang Chen[1]

[1] Regional Climate Group, Department of Earth Sciences, University of Gothenburg

[2] Bert Bolin Centre for Climate Research, Department of Physical Geography ~~and Quaternary Geology~~, Stockholm University

[3] Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

Correspondence to: Peng Zhang (Peng.Zhang@gvc.gu.se)

~~Resubmitted~~Revised and submitted to Climate of the Past

Abstract

~~New collected Scots pine (*Pinus sylvestris* L.) tree-ring 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. 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 was produced based on 'regional curve adjusted individual signal-free approach' (RSFi) which preserve mid- and long-term signal, and has better potential to remove unwanted noise (e.g. related to stand dynamics) on tree level. The new reconstruction, called C-Scan, 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 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 hemisphere temperature evolution during the last 12 centuries, indicating the warm peak of MCA ca. 1009-1108 CE and the coldest period of LIA ca. 1550-1900 CE in central Fennoscandia. Moreover, in central Fennoscandia, during the past 1200 years, the coldest period was found in the late 17th-19th century with the coldest decades being centered on 1600 CE, and the warmest 100 years occurring in the most recent century.~~

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 a new Scots pine tree-ring density based reconstruction of warm-season (April-September) temperature for central Scandinavia, called C-Scan, back to 850 CE, extending the previous one by 250 years. C-Scan is largely based on pine trees collected in a confined mountain region, where the samples were adjusted for differences in altitude and local environment, and standardised in order to preserve as much mid- and long-term temperature change as possible. C-Scan suggests that the warm peak of MCA occurred in ca. 1000-1100 CE, and points to a Little Ice Age (LIA) between 1550 and 1900 CE. Moreover, during the past millennium the coldest decades were found around 1600 CE, and the warmest 10, 30 and 100 years occurred 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 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 ~~Fennoscandia~~Scandinavia, Last millennium, Maximum late wood density, Scots pine, Warm-season temperature

1. Introduction

In order to assess the role of human activities on the current climate change (Bindoff et al., 2013), numerous efforts have been made to put the present warming in a long-term context (e.g. Wilson et al., 2016). Despite these attempts, there are still some controversies about past climate. For example, global mean temperature may have been as 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 timing as well as magnitude of the MCA (PAGES 2k Consortium). To further improve our understanding of past climate changes, there is still a great need to produce and improve empirical proxy data.

Tree-rings are widely recognized as excellent proxies of growing-season temperatures due to their annual resolution and absolute dating (Briffa et al., 2001). The high latitude region of Fennoscandia in northwestern Europe has a strong tradition in dendrochronologydendrochronological research, and its large tracts of relatively accessible boreal forestforests with some of the world's most temperature sensitive conifers (George, 2014) and favourable preserving conditions of dead wood (see below), make the region well suited for the development of tree-ring chronologies that extendextending back over the last millennium past millennia (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, 2008) and Jämtland (Gunnarson et al., 2003), several millennium--long temperature-sensitive tree-ring datasets were collectedproduced within the European UnionEU funded "Millennium" project (McCarroll et al., 2013). However, these were all, except for the Jämtland and Mora (822-year Blue intensity, Graham et al. (2011)) records, located in northernmost Fennoscandia. It 2013). Due to the superior performances of maximum latewood density (MXD, e.g. Briffa et al., 2002), and the recently developed ΔDensity method (Björklund et al., 2014a; 2015), as warm-season temperature indicators, it has been shown that in order to better these proxies are to be preferred when high-resolution reconstructions of Late-Holocene temperatures are targeted. In Fennoscandia, most sampling for millennium-long temperature reconstructions have been focused to regions close to the latitudinal tree limit (Esper et al. 2012; McCarroll et al. 2013; Melvin et al. 2013). However, to represent Fennoscandian warm-season temperature variabilitythe whole of Fennoscandia with more fidelity, data from more southernsoutherly locations are also needed (Linderholm et al., 2014a). More recently,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 maximum latewood density (MXD) data. In Sweden, 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 MXD from Jämtland (63 ° N; Gunnarson et al. (., 2011,; henceforth G11, referring to the temperature reconstruction) reconstructed 900 years of), 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. Because of the relatively southerly location, Jämtland is considered a key location , 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 paleotemperature studiesthe last 3600 years in central 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 variability (e.g. Cunningham et al., 2013).

At northern high latitudes, MXD is the most powerful warm-season temperature However, the tree-ring proxy (Briffa et al., 2002a, 2002b). The longest Scots pine MXD records have been sampled in northernmost Fennoscandia (see McCarroll et al., 2013; Melvin et al., 2013; Esper et al., 2012; Esper et al., 2014; Matskovsky and Helama,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.

The primary aim of this study was to extend 2014). These chronologies are exclusively based on material with known temperature-sensitive provenience, from living trees, snags and, in the case of N-Scan, subfossil wood (tree remains which have been buried in lake sediments for hundreds or thousands of years) (Esper et al., 2012). G11, however, also included back in time to cover the MCA. Moreover, G11 contained data collected from historical buildings in the Jämtland region in west-central Sweden, which were sampled in the late 1980s as a part of an archaeological survey by Kvartärbiologiska 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 in the northern hemisphere (Schweingruber, 1990). Due to the limited number of dead wood samples at that time from the studied area in the Scandinavian Mountains, theThe historical samples (, covering the period between 1107 CE and 1827 CE, with a gap betweenduring 1292-1315 CE), made up a major part, were combined with samples from living trees and snags (remains of G11. Sincedead trees) collected in the mountains in the early 2000s, yielding a reconstruction spanning 1107–2006 CE. The geographical origins of some of the historical samples in G11 are somewhat unclear, wherebut they likely originatecame from lowland locations, about 300 meters below the present tree-line, it isand should thus not anbe optimal dataset to incorporate in as the backbone of 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 (Fritts, 1976). Therefore, we also aimed at, as far as possible, replacing the MCA in the world (Mann et al. 2008; Pages 2k consortium, 2013). In the central Scandinavian Mountains, tree-ring 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 historical samples with samples during this period.

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 temperaturecollected from past and present tree-line environments where the provenance of the trees was known. Using this new reconstruction and remove uncertainties of sampling provenances in the same. This will enable us to improve the understanding of , we re-examined the warm-season temperature evolution in central Scandinavia during the last 1150 years, and compared it to other reconstructions from northern and eastern Fennoscandia (Melvin et al., 2013; Esper et al., 2012; Helama et al., 2014). during the entire past 1200 years in this region, as well as make a more reliable comparison between the MCA and present conditions.This improved dataset allows us to provide new insight 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 methodmethods

2.1 Study area

The study area is located in the province of Jämtland is located in the westernmost part of central Sweden. The region belongs to the northern boreal zone, and the study area is situated just, east of the main divide of the Scandinavian Mountains main divide. The main topographyin west-central Sweden. Due to the geographical setting, there ranges from 800 to 1000 m a.s.l., and scattered alpine massifs to the south reach approximately 1700 m a.s.l.. There is a distinct climate gradient in the arearegion (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 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, summerthe climate of this particular regionarea is influenced by the atmospheric circulation, mainly 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 this area ranges from 800 to 1000 m a.s.l., and scattered alpine massifs to the south reach approximately 1700 m a.s.l..

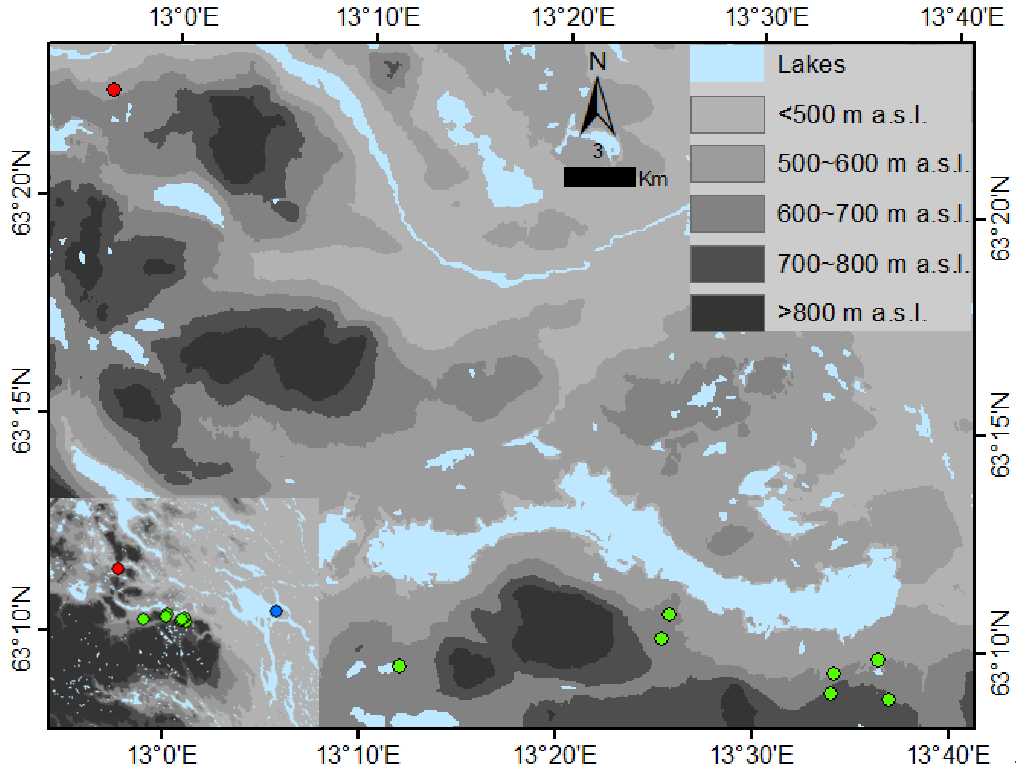
Glacial deposits dominate the area, mainly till but also glacifluvialglaciofluvial deposits, peatlands and small areas of lacustrine sediments (Lundqvist, 1969). The forested parts in the central Scandinavian Mountains are dominated by *Pinus sylvestris* (Scots pine, Norway spruce (), *Picea abies* (L.) H. Karst.). (Norway spruce) and mountain birch (*Betula pubescens*, Ehrh.).. (Mountain birch) are the main tree species in central Scandinavian Mountains. Although large-scale forestry operations have been carried out in mostsome parts of the countyregion, the human impactimpacts 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, snags can be preserved for more than 1000 years on the ground (Linderholm et al., 2014b). Moreover, large amounts of2014) and the subfossil wood fromcan be preserved for hundreds to thousands of years ago can be found in the sediments of small mountain lakes (see Gunnarson (, 2008)).).

2.2 Tree-ring data and data statistics

The Description of the tree-ring data

Scots pine tree-ring samples, collected from seven sites in the central Scandinavian Mountains and from historical buildings 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 of 200m with slightly different moisture-environments ranging from relatively well drained soils to wetter lake-shore conditions. The historical-building samples used in this study was sampled at eight sites (Table 1). As shown in were collected from buildingsFig. 1, they are all in close proximity to each other, but differ in the southeast of Jämtland. Altogether, 99 samples from both living trees and snags were collected from Mount Furuberget at an elevation and local environment. From the small peak Furuberget, 142 samples were collected close to

~~the top at~~ of ca. 650 m a.s.l~~. in an~~.. The sampling sites were characterized by open pine ~~forest~~forests with limited competitions between ~~trees. Pine~~the trees ~~grow on a relatively flat area covered by a~~. The sampling sites had thick vegetation ~~layer~~layers with woody dwarf shrubs and mosses. ~~The area is characterized by thin till and glacifluvial soils.~~Out of the 99 samples, 35 ~~of these samples~~ were ~~included~~previously used in the G11 ~~(Table 1). In addition, pine~~reconstruction. An additional 40 samples, mainly from snags, were collected ~~at different elevations on~~from the nearby Mount Häckervalen, on elevations ranging from ~~the~~ 650 m a.s.l. (present-day tree line ~~(at around 650 m a.s.l.)~~in the area) up to 800 m a.s.l~~., described in detail in~~. (Linderholm et al~~. (2014b). Samples preserved in~~., 2014). 32 samples from subfossil wood collected from the small mountain lakes ~~(subfossil wood) were included from the lakes~~of Lill-Rörtjärnen, Östra Helgtjärnen and Jens-Perstjärnen, ~~and have previously been described in~~ at 560, 646 and 700 m a.s.l. respectively (Gunnarson~~ (~~, 2008~~).~~), were also included. The historical ~~tree-ring data, collected~~samples from ~~historical buildings in~~Bodsjö, which made up the ~~province~~older part of G11, was downloaded from the International Tree-Ring Data Bank (ITRDB). The MXD values of the historical samples have been previously obtained using DENDRO2003 X-ray instrumentation from Walesch Electronic (www.walesch.ch). Table 1 provides a full description of the sampling sites and tree-ring data.



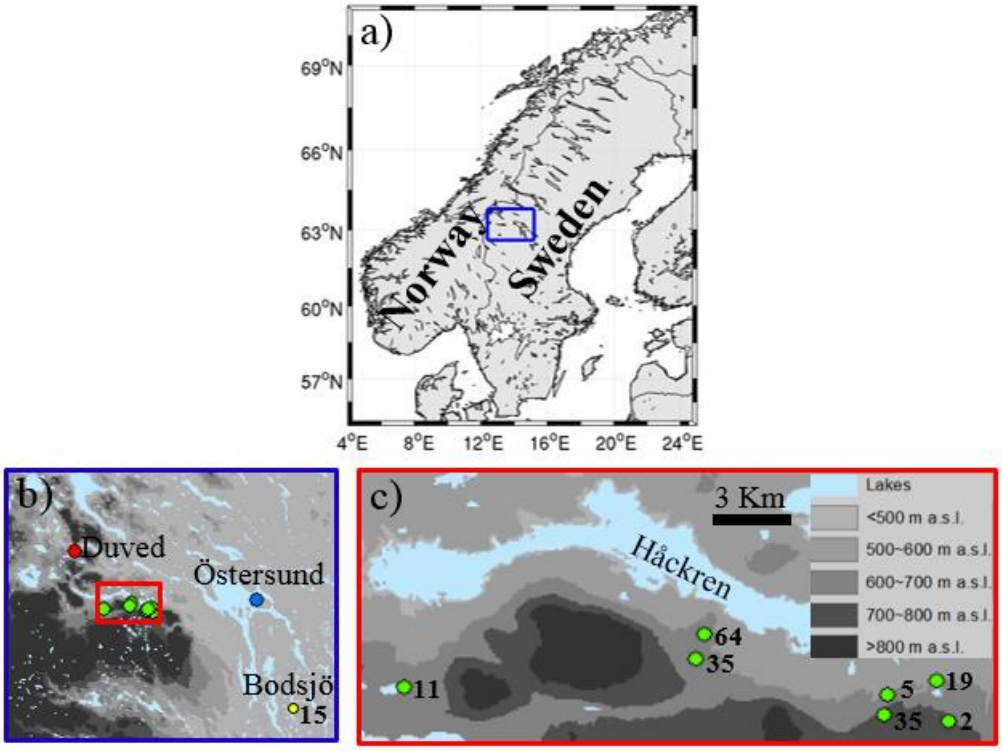


Figure 1. *Map showing the locations of ~~tree-ring sampling sites~~(a) the study area and (b) the sites of the mountain Scots pines (green dots), ~~except for~~ historical buildnings (yellow dot) samples~~,~~ used in this study, and the meteorological stations Duved (the red dot) and Östersund (the blue dot~~) meterological station.~~*

). (c) shows the topography of the mountain Scots pines. Numbers in (b) and (c) indicate the

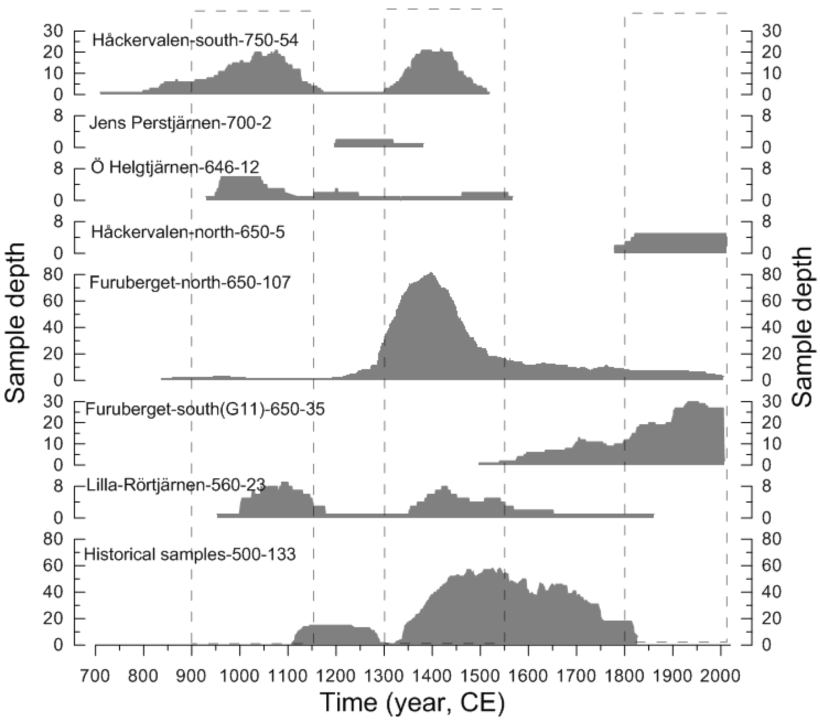
Table 1. Tree-ring sampling sites and summary statistics of the MXD data.

Sampling sites	Elev	TS	NS	MTA	AMXD	MS	AC1
Furuberget-north	650	837-1112	3	156	0.74	0.118	0.566
		1189-2005	104	168	0.69	0.122	0.571
Furuberget-south (G11)	650	1497-2008	35	193	0.64	0.133	0.457
Håckervalen-south	750	783-1265	30	130	0.66	0.125	0.415
		1276-1520	24	113	0.60	0.134	0.449
Håckervalen-north	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	-	-	-
Ö 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 (Jämtlan, Sweden)	≈500	1107-1291	15	158	0.84	0.082	0.676
		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 Furuberget-north, Håckervalen-south, Håckervalen-north, Lilla-Rörtjärnen, 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. *collected from each site.*

The new MXD samples (Table 1) were measured at the tree-ring laboratory of Stockholm University using anthe ITRAX wood scanner from Cox Analytic SystemAnalytical Systems (http://www.coxsys.se). 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 put in a Soxhlet apparatus with pure alcohol to remove resins and other compounds were extracted with pure alcohol in a Soxhlet apparatus.. After being extractedprocessed in the Soxhlet for at least 24 hours, the laths were acclimatized in a room with controlled temperature and humidity to have ca. 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 30kV and 50mA, with 75ms steptimestep time. The opening time of the sensor slit was set to 20µm at each step. From the detected X-ray radiationsensor, a 16-bit, greyscale, digital image with a resolution of 1270 dpi was capturedproduced. The grey levels of the image were calibrated to values of wood density using a cellulose acetate calibration wedge provided by Walesch Electronics. The tree-ring MXD data were analysed withwas obtained using the image processing software WinDENDRO.

In Zhang et al. (2015) it was found that the MXD data used in this study, from the study area covering the same time period but originating from various altitudes (Table. 1), likely differ in their mean values due to the environmental temperature lapse rates. In short, the MXD values at higher elevation were found to be systematically lower than those from lower elevation. Moreover, this influence on the MXD values was found to be larger than the temperature differences between warm MCA and the cold Little Ice Age (LIA, 14th-19th century according to Grove (2001)). Consider for example that older deadwood samples are found only different elevations/sites can have systematic differences in terms of mean values. Because the older snag samples in this study were found at progressively higher elevations, even above present day tree line, as in Linderholm et al. (2014b), and that these samples are combined with lower elevation living trees and younger deadwood. If not accounted for, this may introducewell as contrasting growth environments, serious biases to could thus be introduced into an averagedaverage 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 the differences in absolute MXD values caused by elevation and local moisture conditions are not accounted for (Zhang et al., 2015). Therefore, we adjusted the mean MXD values from the 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 of overlap following. Following the recommendations ofprotocol proposed by Zhang et al. (2015). The), we used the mean MXD valuevalues of the samples from Furuberget-north samples, covering for the period 1300-1550 CE, was used as athe reference for the to correct the data (see Table 1 for adjustment of samples from other groups. The choice of values for each site). The Furuberget-north data was chosen as a reference site was based on the criteria of a highbecause it had the highest sample replication and a widewidest temporal coverage.



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 ~~***Figure 2.***~~ 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. S1. To further validate the mean-adjustment of this data material, Fig. S2 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 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.

Table 1. ~~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.~~

Summary of the tree-ring MXD data.

Sampling sites	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
	750	783-1265	30	130	0.66	0.125	0.415	0.112

Håckervalen-south		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 less than 100 years, because the MXD measurement was only a part of a tree-ring width series which was much longer. The temporal restriction of these samples was 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 was downloaded from the International Tree-Ring Data Bank (ITRDB), and was previously used in G11.

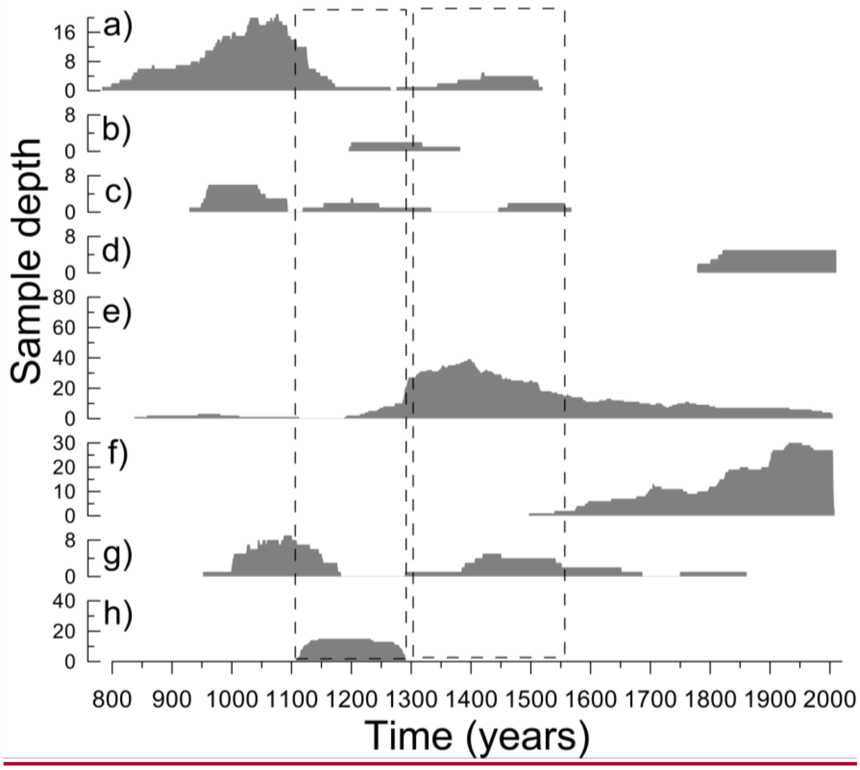


Figure 2. *Sample replication through time at (a) Håckervalen-south, (b) Jens Perstjärnen, (c) Ö Helgtjärnen, (d) Håckervalen-north, (e) Furuberget-north, (f) Furuberget-south (G11), (g) Lilla-Rörtjärnen and (h) Bodsjö. The dashed lines mark the two reference periods for mean-adjustment (see main text).*

2.3 Standardisation ~~and chronology building~~methods

If tree-ring data is going to be used to attain ~~reliable~~high-quality climate information, it is ~~pertinent~~necessary to remove as much non-climatic ~~information~~"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 (Fritts, 1976; Cook and Peters, 1981~~), and subtracted or divided~~). This is subsequently removed from ~~each raw tree-ring measurement to obtain indices used for chronology building,~~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 ~~value~~values of all the tree-ring series ~~will be~~are adjusted to the same level after ~~standardization. This~~standardisation. The limitation on preserving low-frequency variability whose period is longer than trees' mean age 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~~removed from~~ or divided by~~ each individual tree-ring measurement, 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 variability ~~is~~may be 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) ~~show~~showed that using multi-curve RCS can, however, efficiently remove these biases. Alternatively, the non-climatological expression in tree-ring data can be quantified with an individual signal-free (SF) approach~~ to standardisation~~, described in Melvin and Briffa (2008), but this approach is ~~more~~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 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~~ is henceforth referred to as~~, and was termed RSFi. ~~We~~In this study, we produced MXD chronologies ~~with the~~using two standardisation methods: ~~classic RCS, SF RCS (single~~ two-curve ~~and multi-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 ~~with~~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). ~~In this study,~~Here the EPS values were calculated in a 50-year ~~temporal~~ window with ~~25~~a 1-year ~~overlap.~~ lag.

2.4 Instrumental data

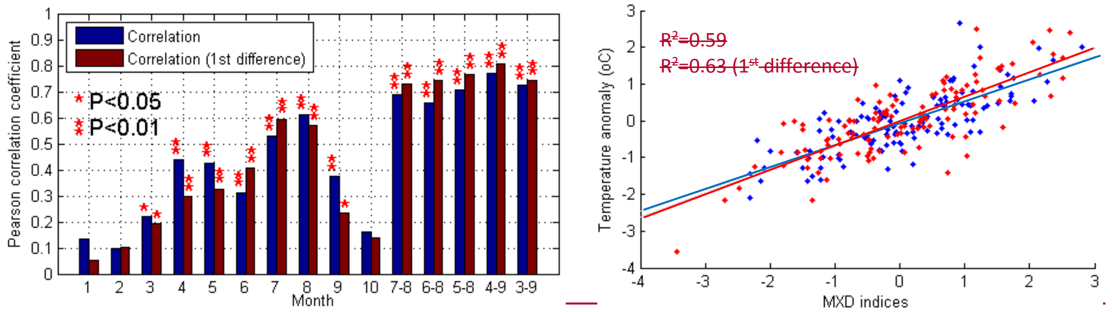
Monthly temperature data from the closest meteorological station, Duved (400 m a.s.l., 63.38 °N, 12.93 °E), was used to assess the temperature signal reflected by the chronology. Since the data from this station only cover the period 1911-1979~~ CE, we~~, the data was extended ~~the data~~ back to 1890 CE and up to 2011 CE~~ by~~ using linear regression on monthly temperature data from an adjacent station: Östersund (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~~explained on average 91.5% of the interannual variance ~~in~~of Duved monthly temperature (based on the overlapping period 1911-1979~~ CE~~). The temperature data from Östersund came from two sources: the Nordklim ~~data base~~dataset (1890-2001~~ CE~~) (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 ~~in the new chronology~~and reconstruction technique

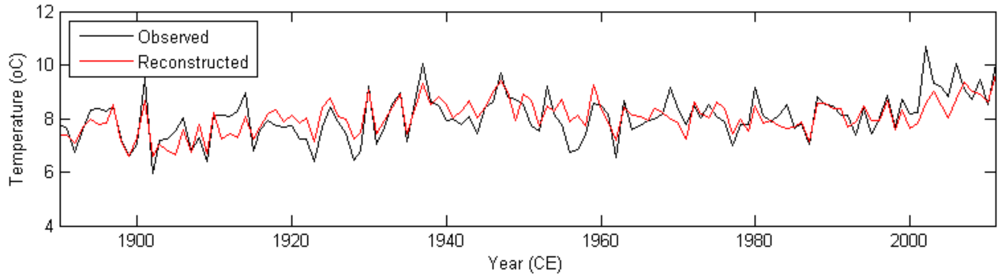
We ~~compared~~calculated correlations between the new MXD chronology ~~with the~~and instrumental monthly mean temperatures ~~constructed for the~~ from Duved ~~meteorological station during~~over the period 1890-2011 CE. Fig. ~~3a~~3 shows that ~~the new chronology has a significant positive correlation (at~~ it is significantly correlated (p~~<~~ < 0.01~~ level~~) with all individual ~~monthly mean temperatures in~~ months from April-~~ to September, and the ~~highest correlation was found~~correlation with mean April-September temperature is 0.77 (0.81 (p<0.01) if only interannual variability were considered). Same results were obtained (0.77, p<0.01) when correlating the MXD chronology with mean April-September temperature ~~(r=0.77). Therefore, we decided to reconstruct~~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~~ 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 (Fig. 3c),~~

anomalies (deviations from the 1961–1990 mean) were set as the predictand and the new MXD reconstruction explains 59%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 the instrumental data (Fig. 3b).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.



(a) (b)



(c)

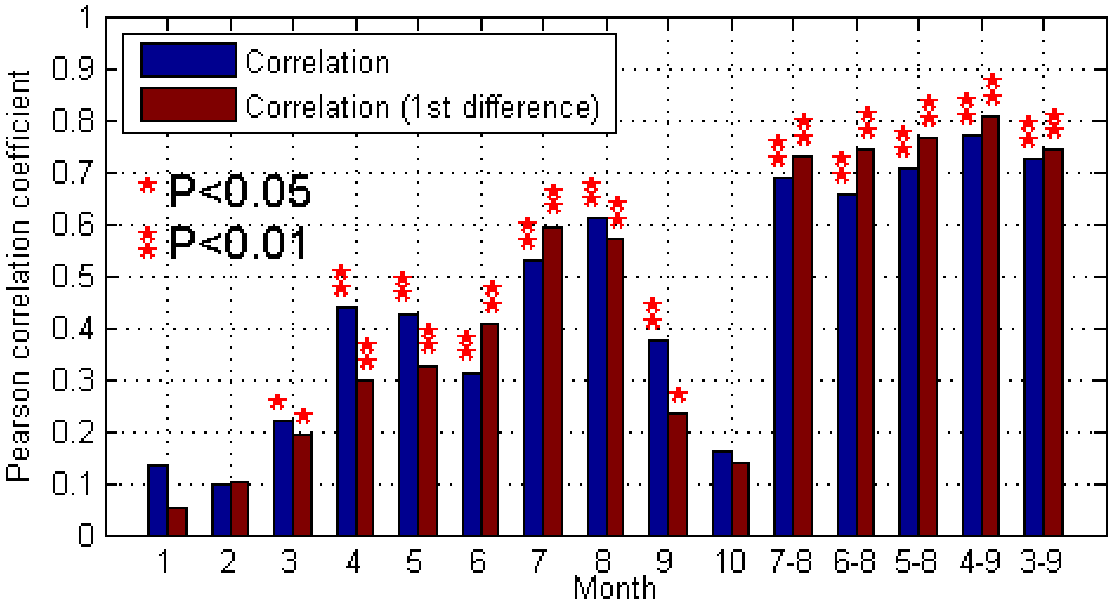


Figure 3. ~~(a) Correlation~~*The correlations between the mean-adjusted MXD* ~~data~~*chronology, standardised with the RSFi method, and observed monthly mean temperatures from Duved meteorological station over the period 1890-2011* ~~CE. Correlations~~*. The correlations are given from January to October of the* ~~growth~~*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. ~~average, (b) linear~~ 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 and multidecadal 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).

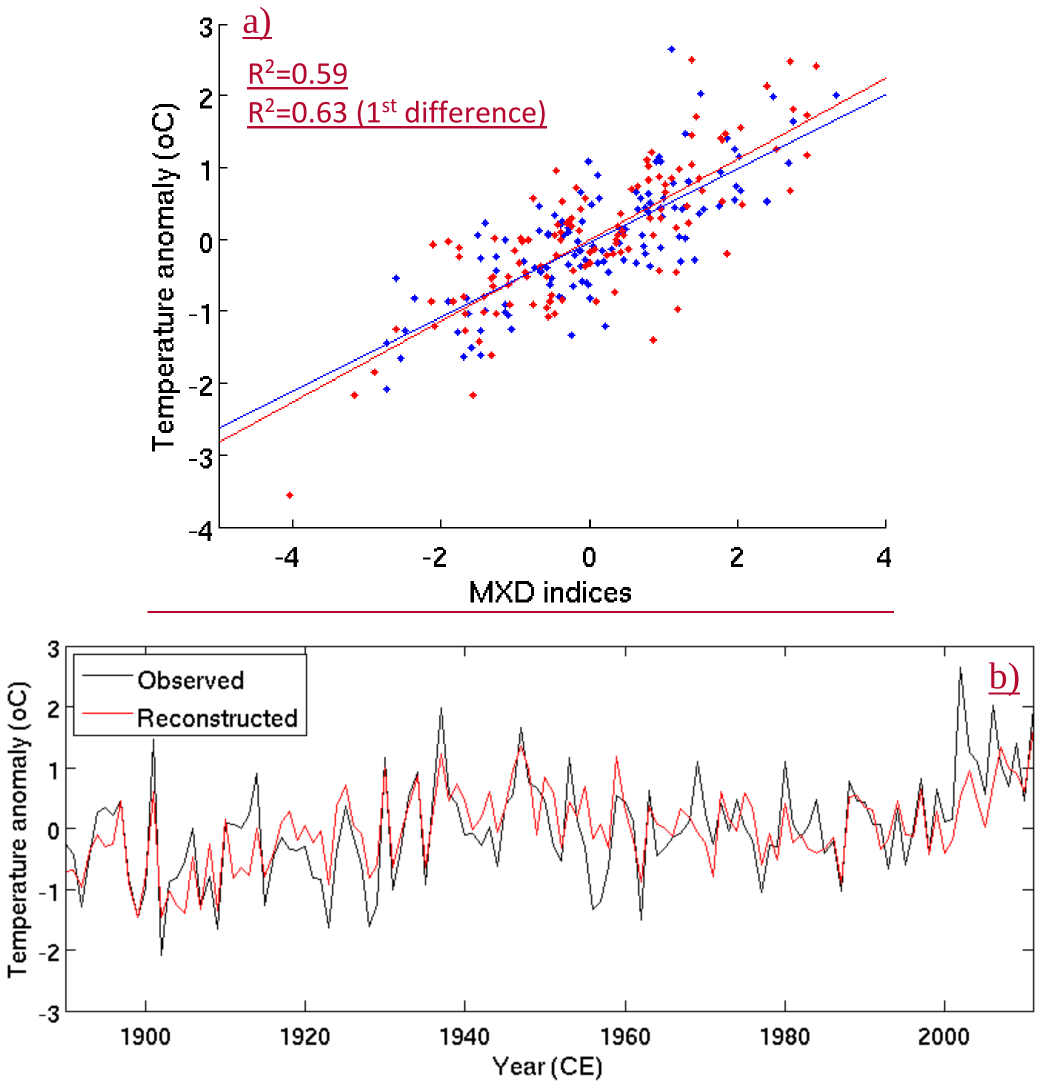


Figure 4. *(a) Scatter plot of the MXD indices versus observed warm-season temperature ~~(anomaly~~ anomalies (relative to 1961-1990 mean) from Duved (blue~~)~~), and their respective 1st difference components (red), and (b) a comparison of reconstructed warm-season temperature (red) ~~with~~and observed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

~~**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 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 –∞ 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.~~

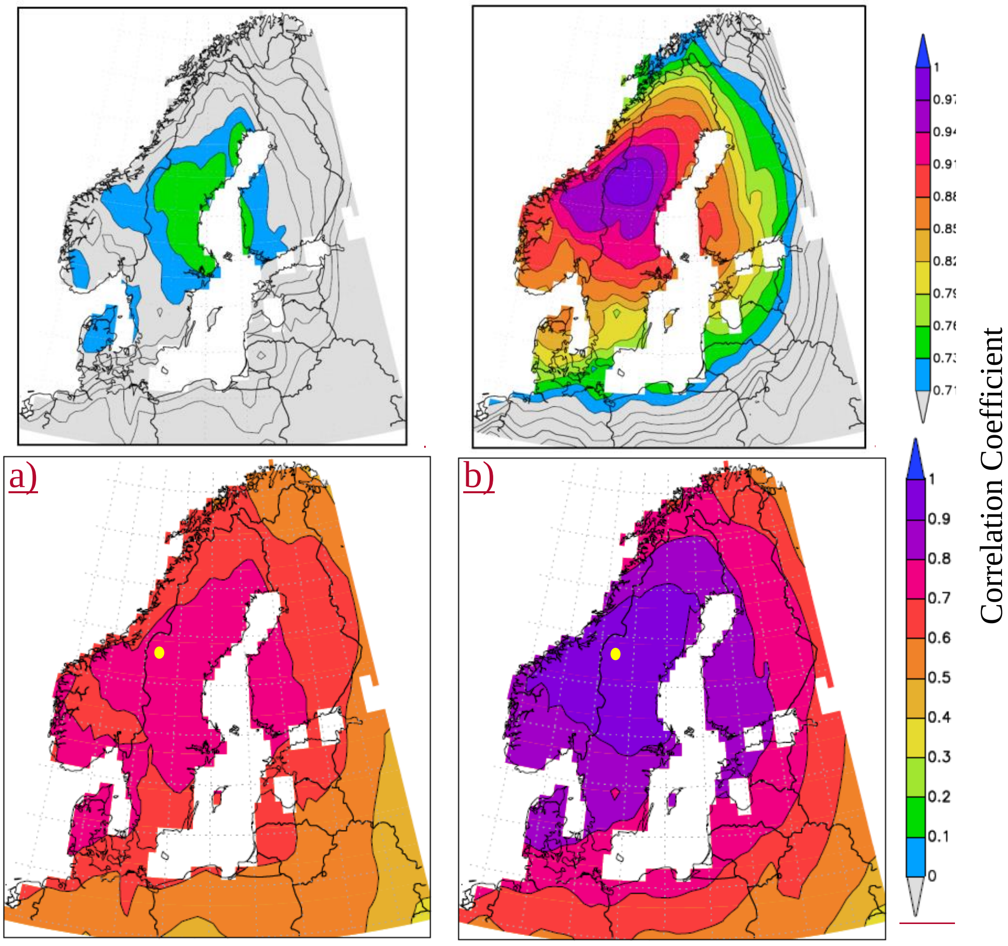
Table 2. ~~Calibration~~*The calibration and verification statistics of the warm-season temperature reconstruction.*

	MXD RSFi chronology		
Calibration period	1890-1950	1951-2011	1890-2011
Correlation, R	0.82***	0.~~67~~68***	0.77***
Explained variance, R^2	0.67	0.~~46~~47	0.59
No. of observations	61	61	122
Verification period	1951-2011	1890-1950	-
Explained variance, R^2	0.~~46~~47	0.67	-
RE#	0.~~55~~56	0.~~71~~72	-
CE#	0.~~44~~45	0.~~65~~66	-
Slope	-	-	0.5703
Intercept	-	-	-0.1453

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

~~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 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.~~



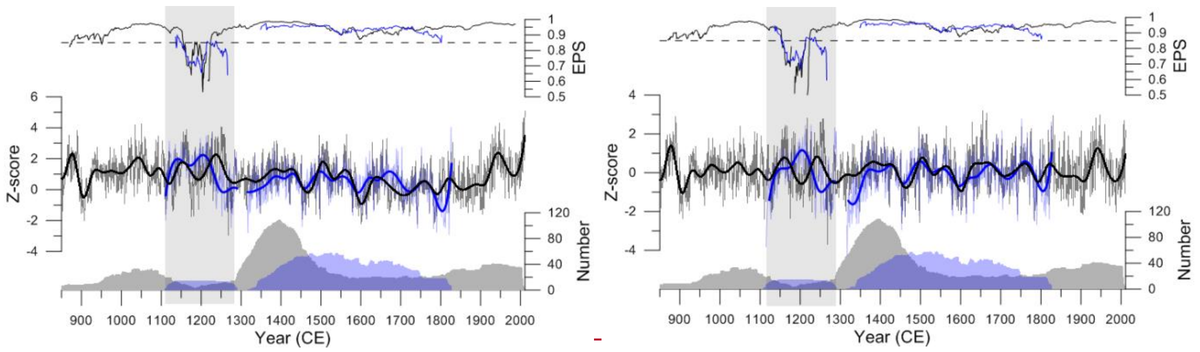
(a) (b)

Figure 45. *Field correlations of the 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 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 1901-2011 CE. Grey areas outside the r=0.71 isoline represent the correlations at p<0.001 significance level.. The yellow dots mark the approximate locations of the sampling sites. The field correlation maps were plottedmade using the 'KNMI climate explorer' (Royal Netherlands Meteorological Institute; http://climexp.knmi.nl; van Oldenborgh et al., 2009).*

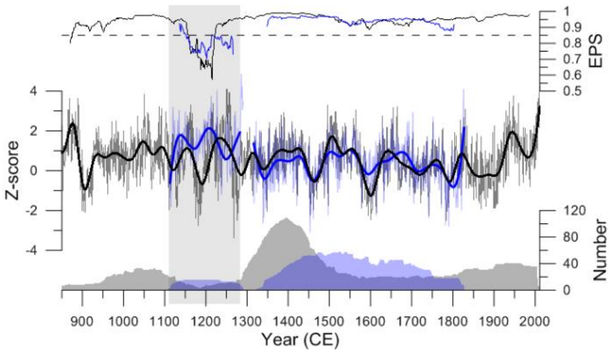
3. Result and discussion

3.1 Comparing MXD samples of different origin

We compared the two chronologies based on the 'in situ' and historical samples respectively. Three standardisation methods were applied to build the chronologies. 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 (5a), negative exponential function standardisation (5b), and RSFi standardisation (5c) 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 explain 34% 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 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 CE, but the EPS of the boosted chronology during 1160-1210 CE was still below 0.85, and the EPS during 1225-1265 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.



(a) Signal-free RCS (b) Negative exponential



(c) RSFi

Figure 5. Comparison of the z-scored (based on 1700-1800 CE) interannual (thin curves in the middle subplot) and 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 with a shaded background.

3.2 The influence of standardisation method

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 three above mentioned RCS methods as well as the RSFi method. As shown in Fig. 6, the difference among the four differently standardised chronologies is mainly reflected in the multidecadal variability. The chronologies produced by the two single-curve RCS methods are in very good agreement on 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 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 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.

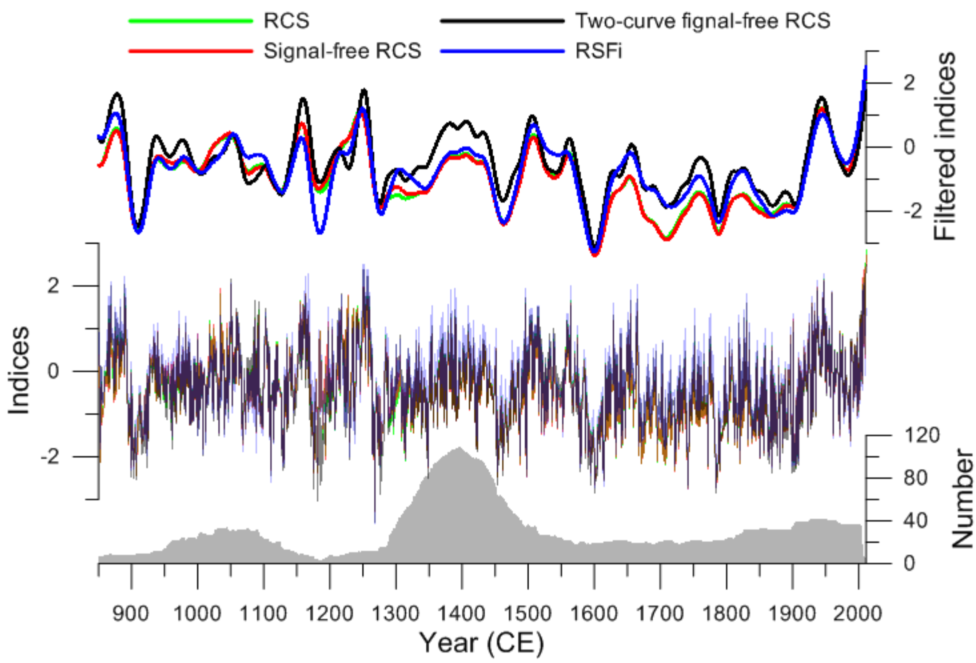


Figure 6. Comparison of the interannual (thin curves in the middle subplot) and multidecadal (50-year spline) (bold curves in the upper subplot) variability in the mean-adjusted 238 field-sample based chronologies based on RCS standardisation (smoothed by hugershoff function) (green curves), one-curve 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 (blue curves). Sample replication was given in the lower subplot.

3.3 Central FennoscandianScandinavian 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. 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 not show obvious differences at interannual (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 similar. 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 in central Scandinavia, henceforth referred to as C-

Scan, during the past ~~1200~~1150 years. C-Scan displays a cooling trend ~~between~~over the period 850~~ CE and 1800 CE ~~-1900, followed by a sharp temperature increase ~~after~~in the ~~mid 19th~~20th 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~~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 La Niña-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 our knowledge about spatial pattern of surface air temperature on global and regional timescales. The new reconstruction will also add values to existing regional temperature reconstructions (e.g. 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 the mid-16th century to ~~early~~the end of the 19th century~~ was the coldest long-term period during the past 1200 years, and that the ~~, where the coldest 100-year period ~~appeared during~~was found in the late 18th to late 19th century. Both the coldest 10- and 30-year periods ~~appeared~~were found around 1600 CE. The warmest 10, 30 and 100-year periods during the ~~17th~~last millennium were all found in the 20th century. ~~The warmest 100 years coincides with the most recent 100 years, which is consistent with the anthropogenic warming period (Stocker et al., 2013). However, ~~Comparing the MCA to the 20th century, the warmest 10- and 30-~~year periods were found in the 13th century. Comparing the MCA with the current warming period showed that the warmest ~~ and 100-year ~~period during~~in the ~~MCA was~~20th century are 0.3 ℃, 0.1 ℃ ~~cooler than ~~and 0.03 ℃ warmer in the 20th century than those in the 10th and 13th centuries respectively.

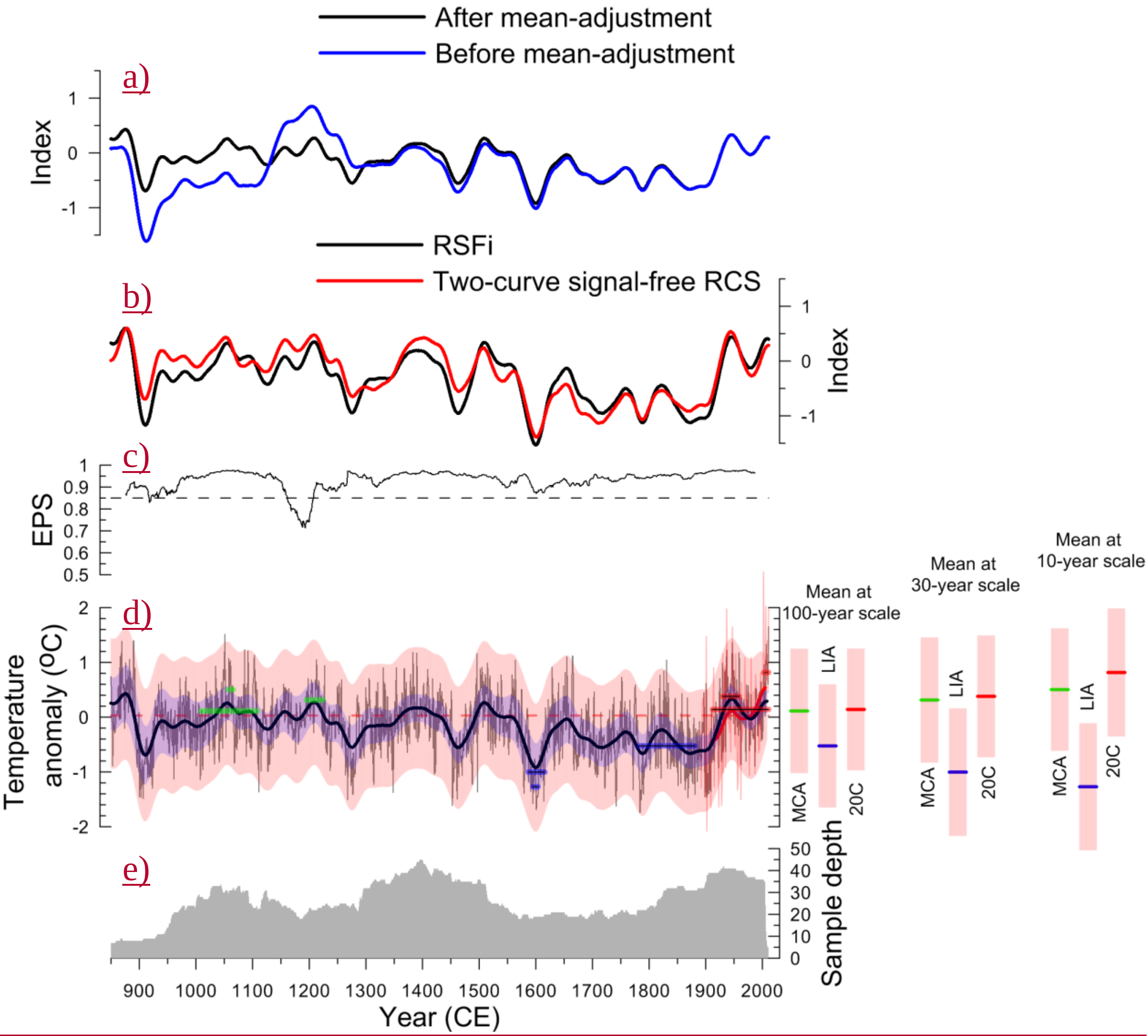
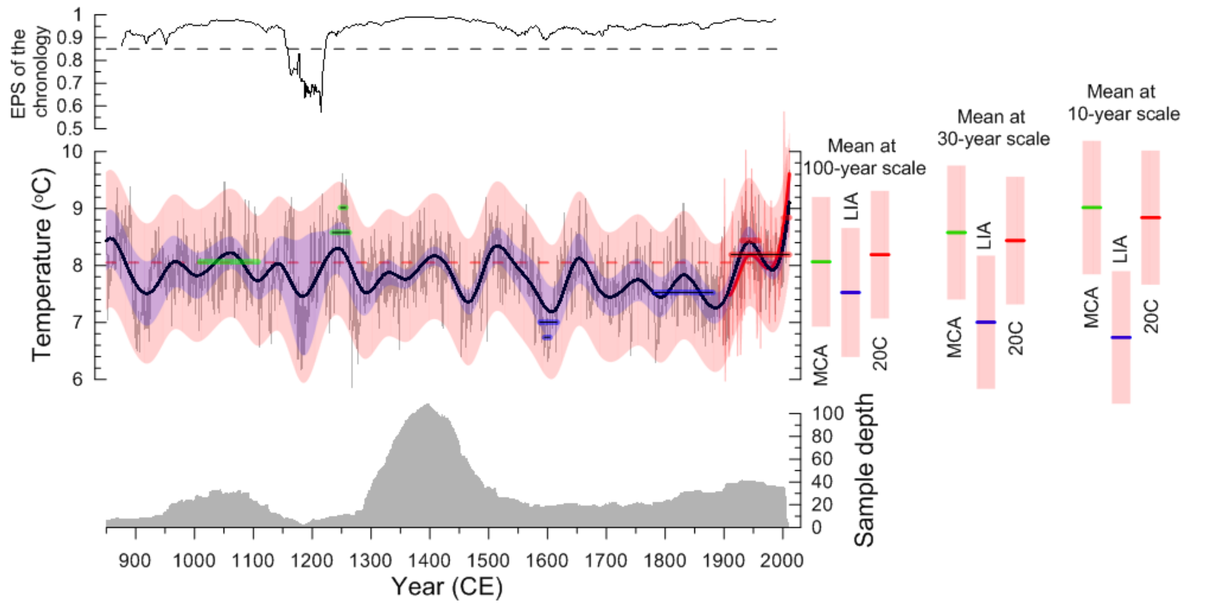


Figure 6. -Characteristics of the central Scandinavian MXD chronology and the resulting warm-season temperature reconstruction: (a) The warmest 10- and 30*MXD chronologies based on samples without mean-adjustment (blue) and after mean-adjustment (black). (b) Comparison of the multidecadal (after 51-year* 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-year periods have EPS values above 0.85.



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~~**Figure 7.** Annual (grey) and 80-year spline~~ *filtered (bold black) warm-season temperature variability in central Scandinavia over the period 850-2011*~~CE inferred from the new chronology in this study. Purple and pink shading indicate~~*. Also indicated is the chronology uncertainty (purple shading) and the total uncertainty of the reconstruction (*~~including~~*pink shading. This includes chronology uncertainty and reconstruction uncertainty*~~), as~~*) expressed as* ~~the~~*+/- 2 times the standard error*~~in their upper and lower limitations. The 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~~*temperatures are shown by the thin red* ~~curve~~*(annual) and the bold* ~~curve~~*red (after 51-year Gaussian filtering) curves, with the red dashed line indicating the 1961-1990 mean. The short lines* ~~in~~*to the right* ~~part~~ *of* ~~the~~ *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.*

~~**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 12^th^ century clearly differs~~7 shows a comparison 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 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 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; Matskovsky and Helama, 2014), as well as for the extra-tropical northern hemisphere (Christiansen and Ljungqvist, 2012).

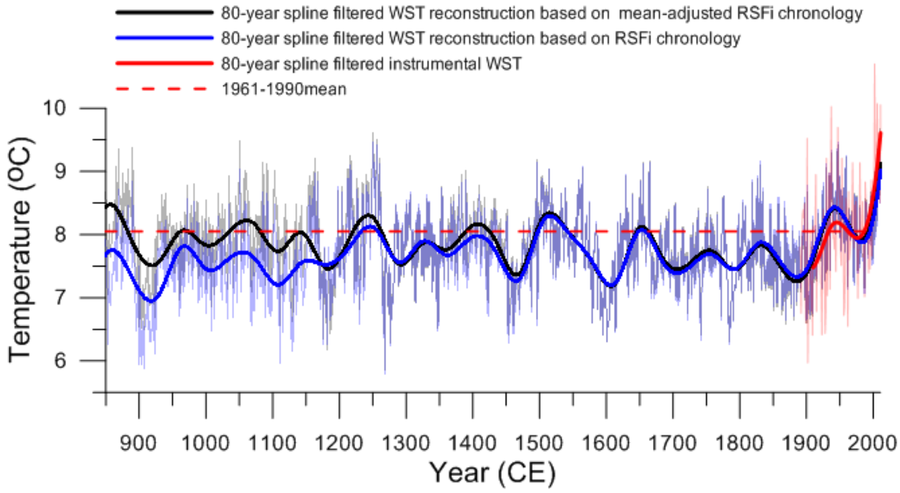


Figure 8. Comparison of the reconstructed warm-season temperature based on the mean-adjusted MXD samples (black) and the unadjusted MXD samples (blue). Red curves show the observed warm-season temperature variability. Light curves indicate the interannual variability, and the bold curves show the variability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

A previous way to deal with samples of different origin (living trees, subfossil and historical wood) or different sites, has been to use separate RCS curves for each type of sample (Gunnarson et al., 2011; Esper et al., 2012), but the prerequisite is that samples of different origin 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 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 reconstruction after the mid-13th century, it provides a mean temperature for 850-900 CE and 1150-1250 CE that is 0.2 °C lower than by our preferred method.

3.5 Comparing C-Scan with the previous central Scandinavia tree-ring MXD warm-season temperature reconstruction

C-Scan was compared with and G11, and as shown in Fig. 9, the 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 centurycentennial 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. However, the 12th century is portrayed as much warmer in G11 duringthan 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 period, it still shows low inter-series correlation (see 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 to centennial timescales. Considering the performance of the 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 following a rather strong regeneration phase during 1200-1350 CE. The strong regeneration of pine may result from successful establishment with good seed production on ground where is dominated by vegetation complexes favorable for seedling growth (Zachrisson et al., 1995).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 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. 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 based on 73% historical samples. Even though the historical samples seemingly perform in a similar way as the tree-line samples, trees at the limit of their distribution should be more sensitive and thus perform better, and be preferred in a reconstruction, 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.

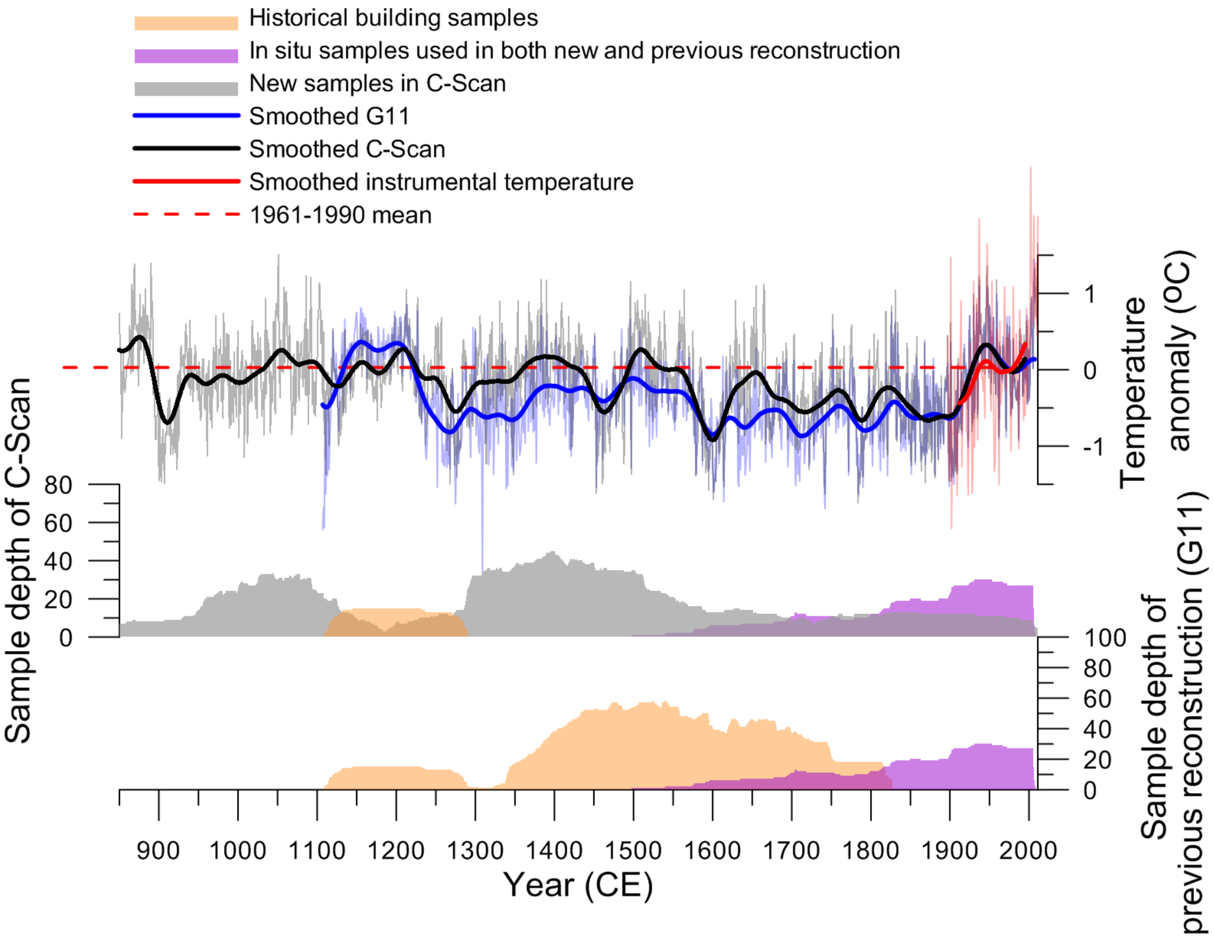
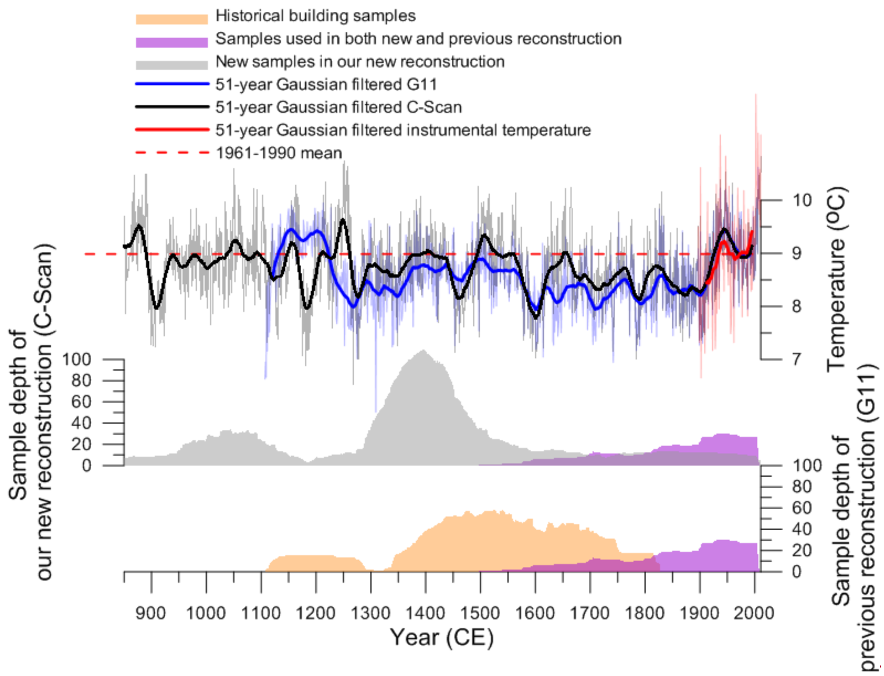


Figure 7.

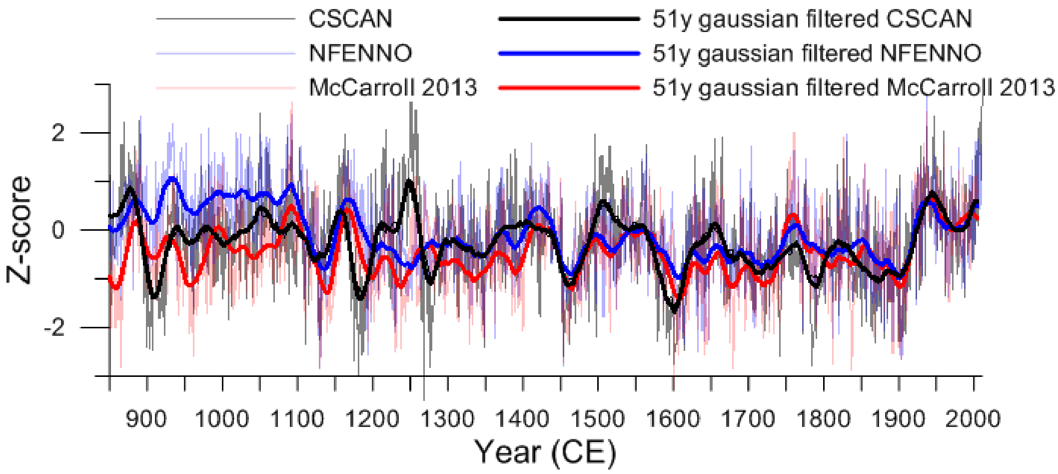


~~**Figure 9**. Comparison of C-Scan (thin grey curve) with the previous tree-ring MXD-based central Scandinavia warm-season temperature reconstruction (~~*A comparison between C-Scan (the thin grey curve) and G11 (the thin blue curve, Gunnarson et al., 2011). Bold black and blue curves show the variability after 51-year Gaussian filtering. The sample depths ~~(number~~ of ~~trees) 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 ~~observational~~observed year-to-year temperature variability (thin line) and its 51-year Gaussian filtered variability~~.~~ (thick line). The dashed red curve ~~marks~~shows the observed 1961-1990 mean warm-season temperature.*

3.~~6~~3 Comparing C-Scan with ~~two northern~~other Fennoscandian summer temperature reconstructions

~~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, except for 19^{th} century, but less agreement before 1300 CE. It is clear that the low sample depth causes the offset during the 13^{th} century, and hence, work on increasing the sample depth of the period before 1300 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 10^{th} – 11^{th} centuries. When comparing C-Scan with the tree-ring multiproxy summer temperature reconstruction from northern Fennoscandia (McCarroll et al., 2013), the latter suggests a similar or slightly colder summer temperature in northern Fennoscandia than in central Scandinavia during 10^{th} – 11^{th} 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 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 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 20^{th} century (Diaz et~~

al., 2011), which support the possibility of differences in regional temperature evolution. Since the instrumental 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.



As mentioned earlier, 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 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 other three reconstructions, because it was calibrated based on longer time-window (i.e. April-September) than the others (MH14: June-July; Mc13: June-August; H14: May-September). The multidecadal variability of H14 generally differs from the other ones, where the pronounced cooling during the LIA stands out. The other segments of the reconstructions agree quite well, although Mc13 in general 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 be 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 circulations patterns 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, the influence of e.g. the Atlantic Multidecadal Oscillation can also be of importance. Furthermore, Irannezhad et al. (2014) found that the trends of observed annual and seasonal surface air temperature show spatial differences in Finland, and that the warm-season temperature can be related to different regional-scale circulation patterns such as the East Atlantic, West Russia, Scandinavian and West Pacific patterns in different sub-region. Thus, it is likely that summer temperature variability in different sub-regions throughout Fennoscandia are controlled by different circulation patterns, and that asymmetric changes of these circulation patterns induce spatial differences in summer temperature evolution. A more detailed study of regional temperature patterns, and their associated regional-scale circulation patterns, in Fennoscandia can 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 analogue to the present warming.

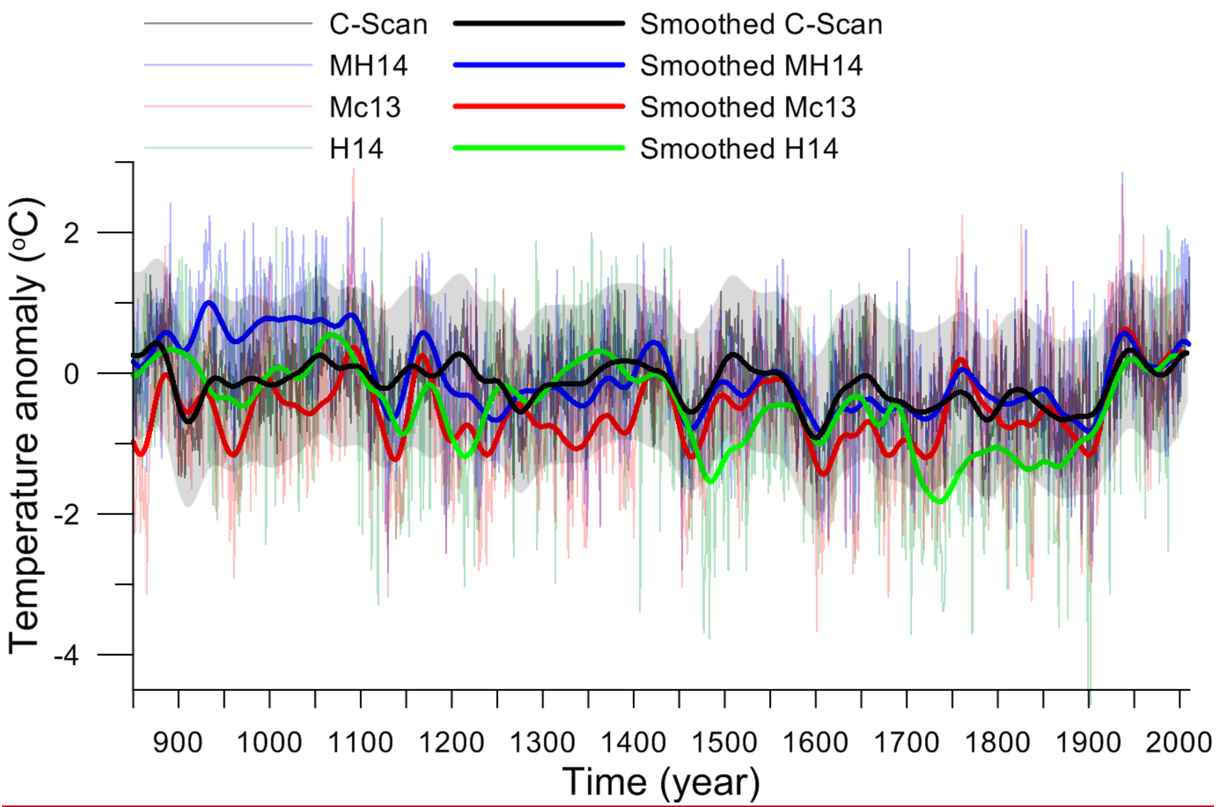


Figure ~~10~~**8.** *Comparison ~~between C-Scan (~~of temperature anomalies (from 1961-1990 period) inferred by four temperature reconstructions covering the whole last millennium: C-Scan (April-September, this study, black~~) with tree-ring)~~, MH14 (June-July, MXD ~~based northern Fennoscandia (NFENNO) summer temperature reconstruction (~~, blue~~) (~~, Matskovsky and Helama, 2014~~) and~~), Mc13 (June-August, multi-proxy ~~based northern Fennoscandia summer temperature reconstruction (~~, red~~) (~~, McCarroll et al., ~~2013).~~2013) and H14 (May-September, MXD, green, Helama et al., 2014). Bold curves show the variability after 51-year Gaussian filtering. ~~Z-scores were calculated based on 1890–2005 CE~~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. 3.7 Comparing C-Scan with an extra-tropical northern hemisphere mean temperature reconstruction

C-Scan 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. 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 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 (Cohen et al., 2012). C-Scan suggests a warm MCA peak between 1000-1100 CE, while the NH reconstruction suggests a longer warm peak between 950 -1150 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, the 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.

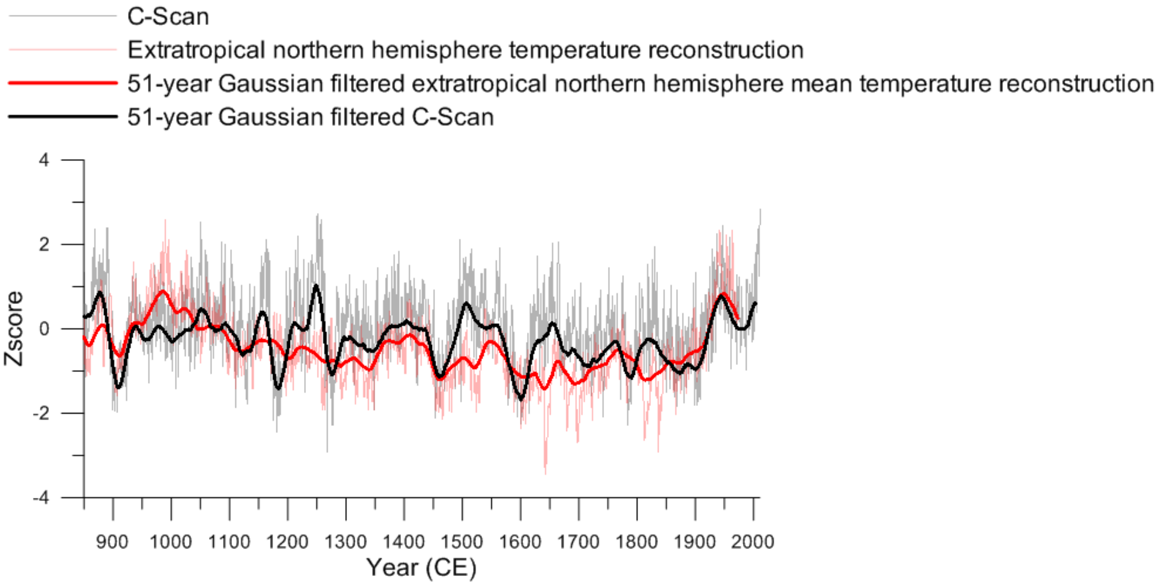


Figure 11 Comparison between C-Scan (thin grey curve) and the extratropical northern hemisphere multi-proxy annual mean temperature reconstruction (thin red curve, Christiansen and Ljungqvist, 2012) during 851-1973 CE. Bold black and red curves show the variability after 51-year Gaussian filtering. Z-

~~scores were calculated based on 1850-1973 CE.~~

~~4. Conclusion~~

~~An~~Conclusions

In this study we successfully updated and extended ~~version of~~ the ~~Jämtland~~ MXD ~~chronology was~~ data previously used to reconstruct ~~the~~ central Scandinavian warm-season ~~mean temperature (April-September) evolution in central Fennoscandia for the period 850-2011 CE. Due to the fact that the samples come from different elevations, the~~temperatures. The new reconstruction, ~~called~~ C-Scan, ~~was based on mean-adjusted data subsequently standardised using the RSFi method. Our new~~now extends back to 850 CE including also 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~~, followed by a transition period before the onset of the Little Ice Age proper~~ in central Scandinavia and a LIA lasting from the mid-16th century to the end of the 19th century. During the last ~~1200 years~~millennium, the late ~~17th~~18th century to ~~early~~late 19th century was the coldest 100-year period in central ~~Fennoscandia, and the warmest 100 years occurred during the most recent century in central Fennoscandia, and the coldest decades~~ Scandinavia, where the coldest 10- and 30-year periods occurred around 1600 CE. The ~~new reconstruction suggests~~warmest 10-, 30- and 100-year periods were found in 20th century. C-Scan indicates lower temperature during the late MCA (ca. ~~1100-1220~~1130-1210 CE) and higher temperature during the LIA (1610-1850 CE) than ~~the previous reconstruction (G11) from the region. Comparing C-Scan to two independent~~ G11.

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

Supplementary

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.

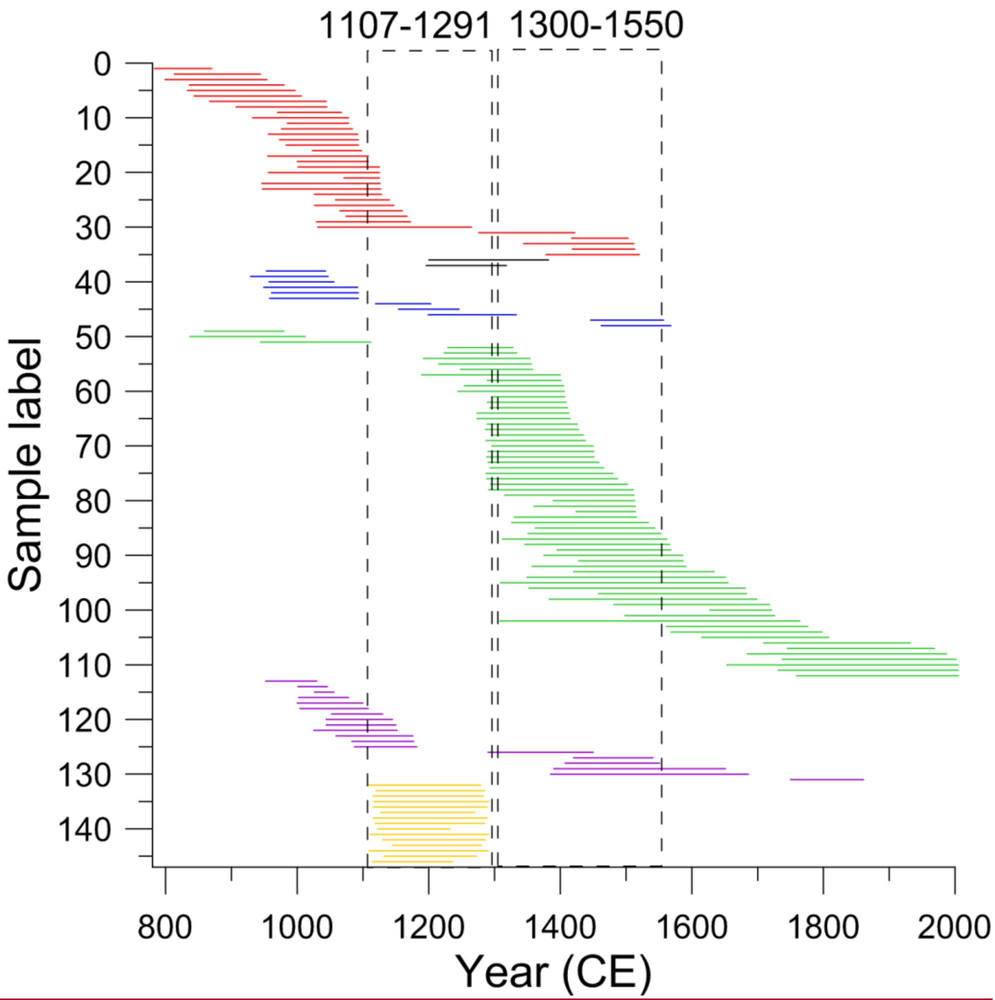


Figure S1. *The time spans of the samples from Håckervalen-south (red), Jens Perstjärnen (black), Ö Helgtjärnen (blue), Furuberget-north (green), Lilla-Rörtjärnen (purple) and Bodsjö (yellow). The samples from* ~~northern Fennoscandia, regional differences in temperature evolution~~ *Furuberget-north which are* ~~notable before~~ *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.*

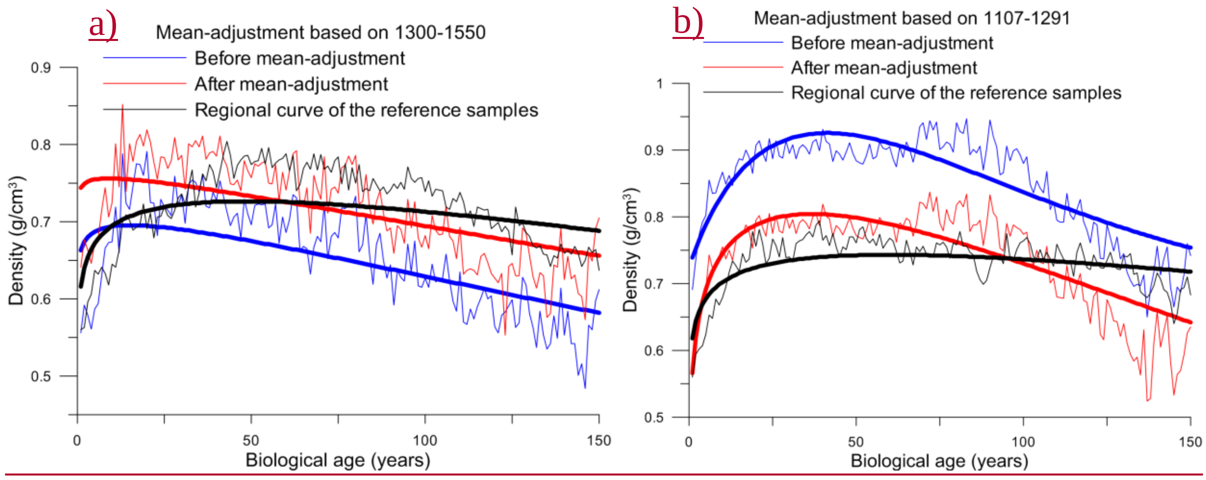


Figure S2. *(a) The smoothed (bold) and unsmoothed (thin) average growth curves of the referenced samples (from Furuberget-north, black) and the samples (from Håckervalen-south, Lilla-Rörtjärnen, Ö Helgtjärnen and Jens Perstjärnen) before (blue) and after (red) mean-adjustment in the common period (1300*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

Acknowledgements

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