

# Quantifying climate changes of the Common Era for Finland

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**Abstract** In this study, we aim to quantify summer air temperatures from sediment records from Southern, Central and Northern Finland over the past 2000 years. We use lake sediment archives to estimate paleotemperatures applying fossil Chironomidae assemblages and the transfer function approach. The used enhanced Chironomidae-based temperature calibration set was validated in a 70-year high-resolution sediment record against instrumentally measured temperatures. Since the inferred and observed temperatures showed close correlation, we deduced that the new calibration model is reliable for reconstructions beyond the monitoring records. The 700-year long temperature reconstructions from three sites at multi-decadal temporal resolution showed similar trends, although they had differences in timing of the cold Little Ice Age (LIA) and the initiation of recent warming. The 2000-year multi-centennial reconstructions from three different sites showed resemblance with each other having clear signals of the Medieval Climate Anomaly (MCA) and LIA, but with differences in their timing. The influence of external forcing on climate of the southern and central sites appeared to be complex at the decadal scale, but the North Atlantic Oscillation (NAO) was closely linked to the temperature development of the northern site. Solar activity appears to be synchronous with the temperature fluctuations at the multi-centennial scale

in all the sites. The present study provides new insights into centennial and decadal variability in air temperature dynamics in Northern Europe and on the external forcing behind these trends. These results are particularly useful in comparing regional responses and lags of temperature trends between different parts of Scandinavia.

**Keywords** Chironomidae · External forcing · Little Ice Age · Medieval Climate Anomaly · Paleoclimate · Paleolimnology

## 1 Introduction

Northern Europe is located between Arctic and Atlantic air masses next to the extensive Eurasian landmass, hence the most important climate gradients are the longitudinal and latitudinal transects. Northern Europe is climatically important because the North Atlantic has a direct influence on the regional climate through the upper troposphere jet stream and strong westerly atmospheric circulation providing the heat and moisture transport from the Gulf Stream (Thompson and Wallace 2001). In addition, continentality is a significant feature in the climate of Northern Europe due to the large eastern landmass of Eurasia that plays an important role also in global climate dynamics and in the amplification of climate change by positive feedbacks (Cohen et al. 2001).

Northern regions are expected to be most influenced by the climate change due to changes in snow and ice coverage and seasonality, for example. The climate change predictions for the 21st century in Scandinavia suggest that warming rates increase along with latitude and distance from the coast (Hanssen-Bauer et al. 2005). Understanding large-scale and long-term climate processes requires

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spatially widely distributed proxy data (PAGES 2k Consortium 2013). In the absence of long-term observed climate data on temperature and precipitation, paleoclimatic records, including those extracted from lake sediments, can be used to reconstruct past climate conditions (Cumming et al. 2012). Paleolimnological methods, including biotic sedimentary proxies such as Chironomidae larvae (*Insecta: Diptera*), which are sensitive to temperature changes, have been found particularly useful to track past climate changes (Brooks 2006; Eggermont and Heiri 2012; Engels et al. 2014). Using the transfer function approach to quantitatively infer air temperature changes, chironomids have been able to track instrumentally measured temperature changes over the meteorological observational period (Self et al. 2011; Larocque-Tobler et al. 2015) and to estimate regionally divergent temperature trends across Europe in the past (Heiri et al. 2014).

In Northern Europe, multi-decadal variations in climate have been indicated to originate from the Atlantic Ocean (Visbeck et al. 2001; Sutton and Hodson 2005). These recurring and persistent climatic teleconnections explain a major part of the variability in atmospheric circulation. There exists a modern (decadal) positive correlation between the North Atlantic Oscillation (NAO) and temperature during summer in eastern Scandinavia (Luoto and Helama 2010). Previous studies suggest that this phenomenon may have prevailed also during a major part of the past millennium (Helama et al. 2009a; Luoto and Helama 2010; Luoto et al. 2013). Furthermore, solar minima with patterns in surface pressure and temperature that resemble the negative phase of the NAO appear to drive cold winters in northern Europe (Ineson et al. 2011). It has been suggested that the Little Ice Age (LIA) was coincident with long-term minimum in solar activity (including the Maunder Minimum), while somewhat opposite conditions prevailed during the Medieval Climate Anomaly (MCA) (Jirikowic and Damon 1994). It has also been suggested that the variations in the solar activity could regulate variations in the NAO (Shindell et al. 2001), however, the solar maximum during the MCA has been proposed to post-date the rise of temperatures (Helama et al. 2009b).

The earliest measured climate data from Finland is from the mid eighteenth century (Vesajoki and Holopainen 1998) and thus, indirect methods are needed to reconstruct the past temperature variability prior these measurements, which are also fragmentary. In this study, we aim to quantify late Holocene temperature variability in Northern Europe from three sites at the multi-decadal scale and from another three sites at the multi-centennial scale. For each temporal scale we examined sites from Southern, Central and Northern Finland using fossil chironomid analysis and the transfer function approach. To validate the method and the new enhanced calibration model by

testing its reliability, we first use a 70-year long high-resolution (up to annual) sediment core (Southern Finland), from which we compare chironomid-inferred temperatures with instrumentally measured temperatures from an adjacent meteorological station. The long-term downcore temperature reconstructions with 700- (multi-decadal records) and 2000- (multi-centennial records) year chronologies are compared with potential external forcing, including the NAO pattern and solar activity. With this study, we aim to increase understanding on spatial patterns of climate changes during the Common Era (CE) in Northern Europe and the forcing mechanism behind these climate fluctuations. The results can be important in assessment of the ongoing global change by providing unique background information on long-term temperature changes in this climate sensitive study region.

## 2 Materials and methods

Six lake sediment cores from an 1100 km latitudinal transect were selected for the study (Fig. 1). Sediment profiles covering the past 700 years originate from lakes Hamträsk (Southern Finland), Pieni-Kauro (Central/Eastern Finland) and Nammajavri (Northern Finland), whereas sites covering 2000-year records include Iso Lehmälampi (Southern Finland), Särkkälampi (Central/Eastern Finland) and Vårdöajávri (Northern Finland). The temporal differences are due to variability in core length and sedimentation rates between the sites. Chronologies of the sediment profiles are based on AMS radiocarbon,  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  analyses. The age-depth models (Supplementary Figure) applied here follow those of previously published work, where also the fossil chironomid communities and study site characteristics are described (Luoto et al. 2008; Nevalainen et al. 2008; Luoto and Helama 2010; Luoto and Sarmaja-Korjonen 2011; Luoto and Nevalainen 2015; Rantala et al. 2016).

The chironomid-based mean July air temperature reconstructions for all the sediment downcores used an expanded Fennoscandian calibration model combining several datasets (Luoto et al. 2014, 2016). The temperature gradient in the training set (180 lakes and 129 taxa) varies from 7.9 to 17.6 °C, including subarctic, boreal and temperate lakes. In common with the original models, the new combined model was developed using weighted-averaging partial least squares (WA-PLS) technique that outperformed other standard model types. The usefulness of additional calibration regression components was assessed using randomization *t* test. In the reconstructions, sample-specific errors (eSEP) were estimated using bootstrapping cross-validation (999 iterations).

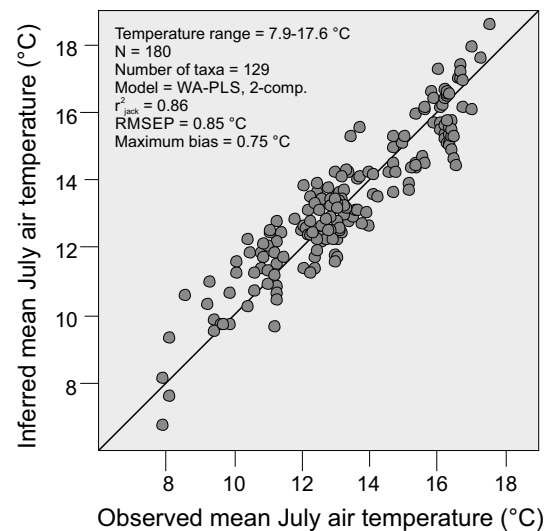
The chironomid-based temperature inference model was validated using a high-resolution (1–2 years) chironomid



**Fig. 1** Study sites in Southern (Tiiläänjärvi, Iso Lehmälampi and Hampträsk), Central (Pieni-Kauro and Särkkälampi) and Northern (Nammajärvi and Värddoajjärvi) Finland in relation to vegetation zones

stratigraphy from Tiiläänjärvi, Southern Finland (Fig. 1, Luoto and Ojala 2014), to assess whether the model reliably tracks summer air temperature variability. The chironomid-based mean July air temperature estimates were compared with instrumentally measured mean July air temperatures from the Kaisaniemi meteorological station (located ~58 km southwest from Tiiläänjärvi) since 1940 CE. The relationship between the chironomid-inferred and instrumentally measured temperatures was assessed using Pearson product-moment correlation coefficient and the level of statistical significance ( $P \leq 0.01$ ).

LOESS smoothing (span 0.2–0.3 depending on resolution) was applied for the reconstructed temperature values to reveal general trends. These trends in the six long-term records, divided into three 700-year decadal-scale and three 2000-year centennial-scale reconstructions from Southern, Central and Northern Finland, were compared with a ~1000-year winter NAO reconstruction based on a



**Fig. 2** Relationship (1:1) between instrumentally measured and chironomid-inferred mean July air temperatures in the new expanded Finnish calibration model

speleothem precipitation proxy from Scotland and a tree-ring-based drought proxy from Morocco (Trouet et al. 2009) to assess the possible influence of NAO as a driver for the reconstructed temperature changes in Northern Europe. In addition, solar activity (total solar irradiance, TSI) based on several radionuclide records from different sites and of different types ( $^{10}\text{Be}$  from Antarctica and Greenland,  $^{14}\text{C}$  from tree rings) (Steinilber et al. 2012) were used for the testing of potential forcing. These data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (<http://www.ncdc.noaa.gov>).

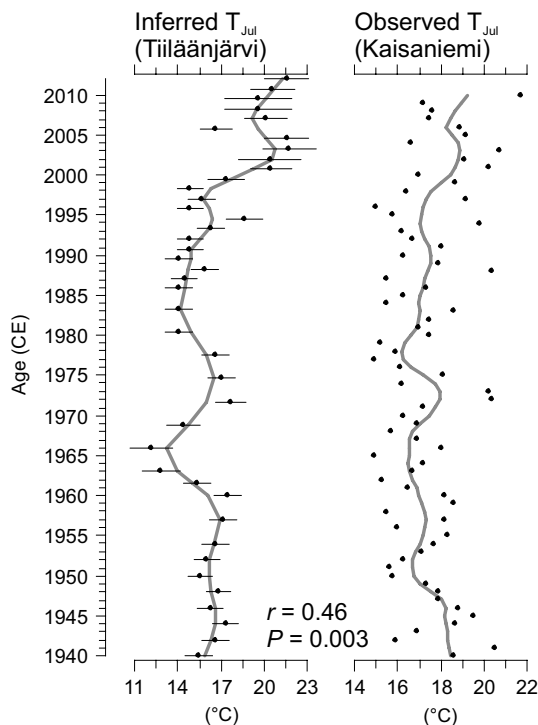
To divide the temperature records according to distinct climate periods and to assess the spatiotemporal patterns of the events, hierarchical constrained cluster analysis was applied using paired group algorithm and Euclidean similarity index. Air temperature anomalies from the reconstructed mean values were used for easier comparison between the southern, central and northern sites.

### 3 Results

The constructed 2-component WA-PLS model had an  $r^2_{\text{jack}}$  of 0.86, a root mean squared error of prediction (RMSEP) of 0.85 °C and a maximum bias of 0.75 °C. Due to increased number of sites compared to the original calibration set, the addition of the second WA-PLS component increased the model's performance by 17.0% with randomization  $t$  test significance of 0.001 (Fig. 2). In the validation of the new model, a significant correlation ( $P = 0.003$ ,  $r = 0.46$ ) was found between the reconstructed July temperatures from the

Tiiläänjärvi sediment record and instrumentally measured July temperatures from Kaisaniemi Meteorological Station since 1940 CE (Fig. 3). For example, the warm periods in 1940s, 1950s, 1970s and early 2000's were clearly reflected also in the chironomid-inferred reconstruction with cooler years in between.

In the 700-year long temperature reconstructions at decadal/subcentennial temporal resolution, there was a common slight decreasing trend from 1300 CE until 1400 CE (Fig. 4). In the southern lake Hampträsk, the decreasing trend continued until 1550 CE, whereas in the central/eastern lake Pieni-Kauro and the northern lake Nammajavri, the temperature increased at 1500–1550 CE. In the southern site, temperature increased later, at 1600 CE, after which all sites experienced a cooling trend. In the southern and central sites, temperatures increased at 1800 CE, but the northern site remained cool until the end of the nineteenth century. A slight cooling occurred during the early twentieth century in the southern and northern sites, but the recent warming (since late twentieth century) was clearly observed in all sites, though with differences in temporal resolution.



**Fig. 3** Comparison between chironomid-inferred mean July air temperatures from the Tiiläänjärvi sediment profile and instrumentally measured July temperatures from the Kaisaniemi meteorological station in Helsinki. The sample-specific errors for the reconstruction are assessed using bootstrapping cross-validation and the trend lines use LOESS smoothing

The centennial-scale reconstructions of the past 2000 years showed a decreasing trend in temperatures until 600–700 CE in Iso Lehmälampi (south), Särkkälampi (central) and Värddoajjärvi (north) (Fig. 5). Between 800 and 1100 CE, the temperatures were elevated in all sites. The reconstructions at the southern and northern sites showed higher temperatures until 1200 CE, but temperature decreased at the central site already before that and continued to be low until 1750 CE. After the coherent cooling, temperatures began to increase towards the present in all sites around 1800 CE.

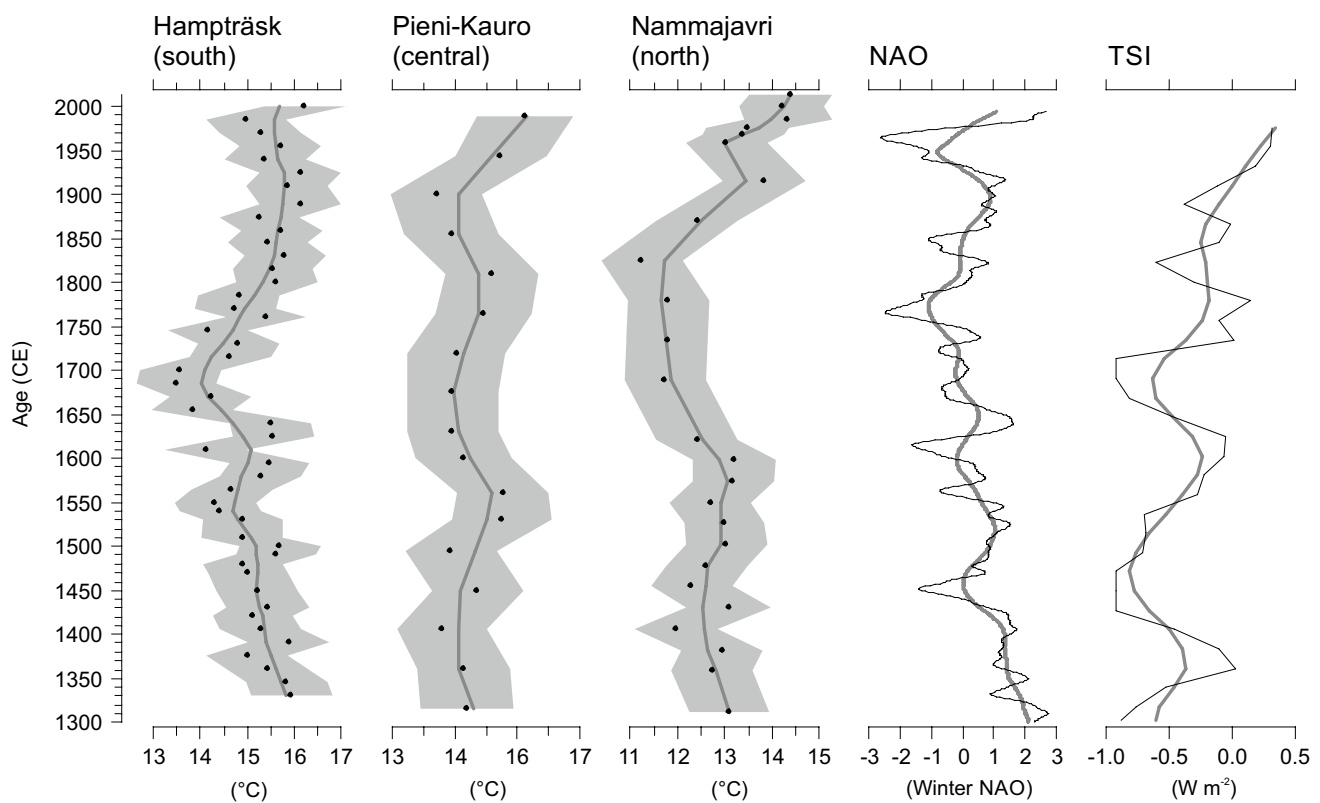
The comparison between external forcing (NAO, TSI) and climate development at the decadal-scale is illustrated in Fig. 4 and at the centennial scale in Fig. 5. NAO index exhibited a long-term trend toward more negative values until ~1750 CE and an increase until 1950 CE. It decreased again around the mid twentieth century and turned to highly positive values during the late twentieth century. Solar activity exhibited a long-term increasing trend between ~1500 and 2000 CE with periods of low insolation during 1450–1550 CE and around 1700 CE with highest values during the late twentieth century.

All records exhibited a signal of the LIA, determined using constrained cluster analysis (note that sample resolution influences the scores), although with clear spatiotemporal differences (Fig. 6). In Southern Finland, the LIA was not uniformly cold but divided into two separate cooling periods with peak temperatures during the sixteenth and seventeenth centuries. In Central Finland, the cool period corresponding with the LIA began earlier, immediately after the MCA, and lasted longer, until the onset of the twentieth century warming. Similar to south, the extent of the LIA was relatively short in the north, although it began shortly later during the seventeenth century and ended at the same time as in the central site at the initiation of the twentieth century warming.

## 4 Discussion

### 4.1 Proxy validation against meteorological data

The expanded chironomid-based temperature calibration model showed favorable performance statistics (Fig. 2). Compared to the previous Finnish models on which the new model builds on, the extended calibration set has increased number (total 183) of sites (see the new sites in Luoto et al. 2016) and taxa involved (total 129 taxa), together with a larger temperature gradient (9.7°C). This provides wider applicability and increases the reliability of the model in downcore reconstructions. The model has higher explanatory power and prediction error compared to the original Fennoscandian altitudinal (Nyman et al. 2005) and



**Fig. 4** Chironomid-based reconstructions of mean July air temperature from lakes Hampträsk (Southern Finland), Pieni-Kauro (Central Finland) and Nammajavri (Northern Finland) since 1300 CE compared with a ~1000-year winter North Atlantic Oscillation (NAO) reconstruction based on speleothems and tree rings (Trouet et al.

2009) and solar activity (total solar irradiance, TSI) based on several radionuclide records (Steinhilber et al. 2012). The sample-specific errors for the reconstructions are assessed using bootstrapping cross-validation and the trend lines use LOESS smoothing

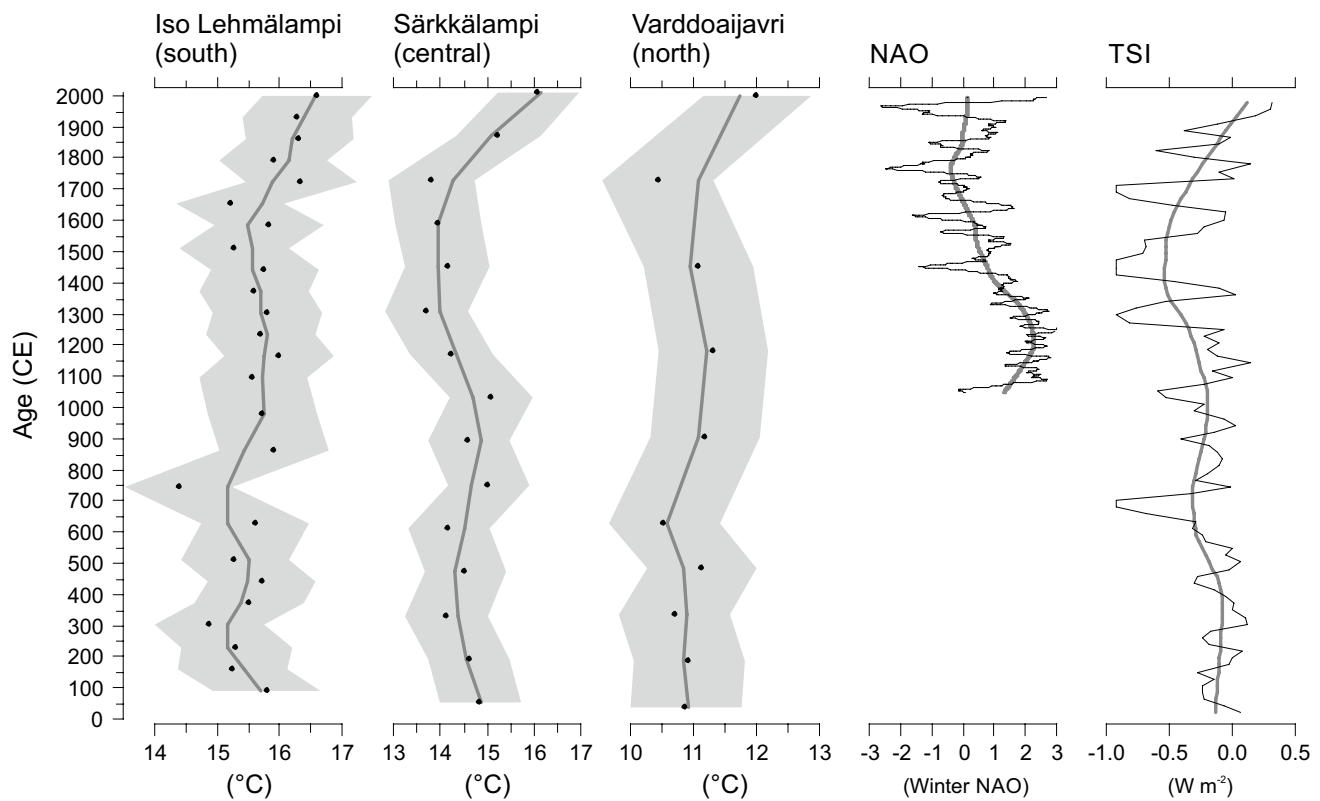
latitudinal (Luoto 2009) calibration models and a decreased maximum error compared to the previous combination of these two calibration sets (Luoto et al. 2014). Compared to the European-wide chironomid-based temperature calibration model (Heiri et al. 2011) constructed for reconstructions of wider temperature ranges, such as between glacial and interglacial periods, our regional model has a similar explanatory power and lower prediction error. Regional datasets, which take into account features of local differences in chironomid communities, likely provide more reliable temperature reconstructions for past periods of more subtle temperature changes (such as the late Holocene).

Previous studies have indicated that chironomid-based summer air temperatures correlate with instrumentally measured temperatures over the observational period in Poland (Larocque-Tobler et al. 2015) and Arctic Russia (Self et al. 2011), for example. In this study, we reconstructed July air temperatures using chironomid assemblages from a high-resolution (up to annual) sediment core from Tiiläänjärvi in Southern Finland (Luoto and Ojala 2014) and compared the results with instrumental temperature record from a nearby meteorological station. A

significant correlation was found between the inferred and observed values and the relationship became even clearer when the data were smoothed (Fig. 3). These results clearly evidence that reliable reconstructions of paleotemperatures from the six selected sediment cores are possible using the new enhanced calibration model. According to Self et al. (2011), chironomid-based inference models should only be applied to sediment cores which have similar climate regimes to the geographic area of the training set. This criterion is fulfilled with respect to all the present study sites.

#### 4.2 Decadal-scale reconstructions of the past 700 years

The reconstructions of the past 700 years (Fig. 4) illustrated generally similar features between the hemiboreal, boreal and subarctic sites distributed along the latitudinal transect in Finland (Fig. 1). However, spatiotemporal differences were also observed. The general features of the LIA are known to be complex and spatially divergent (Mann et al. 2009), though climate was generally cold and summers wet. In western Scandinavia (Nesje et al. 2008) and



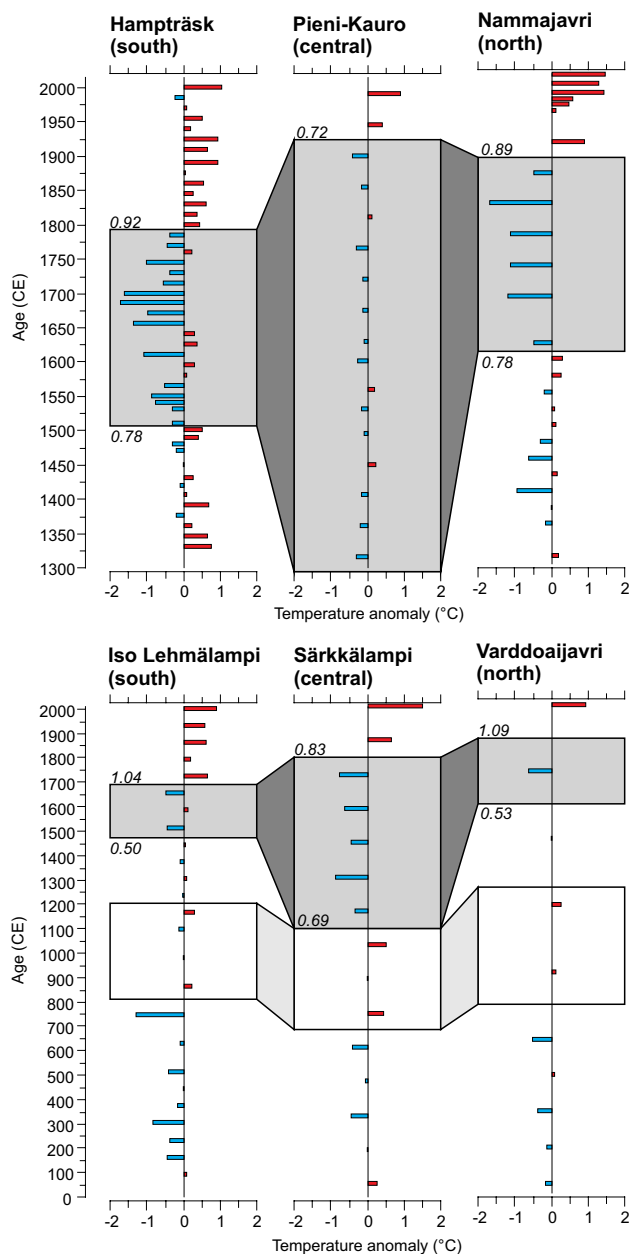
**Fig. 5** Chironomid-based reconstructions of mean July air temperature from lakes Iso Lehmälampi (Southern Finland), Särkkälampi (Central Finland) and Värddoajavri (Northern Finland) since 0 CE compared with a ~1000-yr winter North Atlantic Oscillation (NAO) reconstruction based on speleothems and tree rings (Trouet et al.

2009) and solar activity (total solar irradiance, TSI) based on several radionuclide records (Steinhilber et al. 2012). The sample-specific errors for the reconstructions are assessed using bootstrapping cross-validation and the trend lines use LOESS smoothing

Southern Finland the LIA was characterized by increased precipitation (Tiljander et al. 2003) but in Central/Eastern Finland, the winters were drier than summers (Luoto and Helama 2010). In addition, there were clear temporal differences in the extent and characteristics of the LIA, which generally occurred between 1550 and 1850 CE. These differences are also clearly reflected in our results (Fig. 4). Regionally, the LIA may have initiated earlier, in the beginning of the fourteenth century (Bradley 2000; Grove 2001), such as in our site from Central Finland (Fig. 4), but in general the cooling began in Europe in the mid-sixteenth century (Bradley and Jones 1993) and that the coolest period was the seventeenth century (Jones and Briffa 2001). Tree-ring data from northern Sweden indicate that the coolest period lasted from approximately 1570 to 1750 CE (Briffa et al. 1992), supported also by other proxies from Fennoscandia and adjacent areas (e.g. Hass 1996). However, in our results the timing of the coolest period shows significant variability (Fig. 4).

It has also been suggested that the LIA consisted of two peaks of cold climate conditions in Northern Europe. Tiljander et al. (2003) found from annually laminated

sediments from Southern Finland that during two periods (1580–1630 and 1650–1710 CE) sedimentation rates and accumulation of minerogenic material increased, indicating a wetter and colder climate. Historical data suggest that in 1601–1602 and 1633–1635 CE eastern Scandinavia experienced serious crop failures and in Southern Finland major yield losses occurred also in the late seventeenth century (Rantanen and Kuvaja 1994; Holopainen and Helama 2009). For example, years 1695–1697 were exceptionally cold in Europe (Lindgrén and Neumann 1981) and Finland experienced the greatest crop failures and famine in its history and the crops kept low until the 1720s (Rantanen and Kuvaja 1994). Historical records show that in Central/Eastern Finland the climate remained cold very long and serious famine followed the cold summers in the 1860s and continued until the beginning of the twentieth century (Wilmi 2003). No distinct indication of the general cooler period between 1750 and 1850 CE was found in the southern site (Fig. 4), after which the climate began ameliorating elsewhere in Europe (Osborn and Briffa 2006). Fitting well with the present results, which suggest that cold climate prevailed in central/eastern and northern parts of the



**Fig. 6** Air temperature anomaly (from reconstructed mean) for Southern, Central and Northern Finland at decadal and centennial time resolution. The timing of the Little Ice Age is determined using constrained clustering (Euclidean distance in *italics*) and marked in gray. Due to low number of samples, the clusters for the Medieval Climate Anomaly (visually observed timing marked in white) were not significant

country longer than in the south, Weckström et al. (2006) showed from Northern Finland that the LIA continued until the early twentieth century. However, the low sample resolution in especially the 2000-year records makes detailed temporal comparison difficult in our records.

According to the present reconstructions, recent warming was evident in all sites (Fig. 4). In common with

measured temperature data (Tuomenvirta 2004), the southern and northern sites show that the 1930s were almost as warm as the recent years, but this is not evident at the central site. However, these features could be simply due to the coarser temporal resolution of the central sediment core. In any case, the reconstructed values for the most recent samples were higher than during any past time period in each of the records.

### 4.3 Centennial-scale reconstructions of the past 2000 years

The centennial-scale reconstructions of the past 2000 years showed mutually decreasing trends in temperatures until 600–700 CE and elevated values between 800 and 1100 CE (Fig. 5). The former temperature decrease corresponds with glacier advances elsewhere in Scandinavia (Matthews et al. 2005) and the latter temperature increase with the general timing of the MCA (Esper et al. 2002). Climate at the southern and northern sites remained warm until 1200 CE, but the central/eastern climate cooled slightly before that. The MCA has generally been considered to be warm and dry (Helama et al. 2009a; Nevalainen et al. 2013), though the winters may have been characterized by increased snowfall in eastern Scandinavia (Luoto and Helama 2010). In Southern Finland, the climate gradually dried already from 300 CE onward with the driest period between 800 and 1100 CE (Nevalainen and Luoto 2012), whereas in Eastern Finland a “megadrought” prevailed between 1000 and 1200 CE (Helama et al. 2009a) suggesting differences in hydroclimatic conditions between Southern and Central/Eastern Finland.

Compared to the decadal-scale reconstructions (Fig. 4), the timing of the LIA in the southern sites and the special features including the two separate cooling periods interrupted by a warm event at ~1600–1650 CE, are also represented in the centennial-scale reconstruction. The two-phased LIA is also present in the decadal-scale reconstruction from Northern Finland. Therefore, since these two cooling episodes occur only in Southern and Northern Finland (Figs. 4, 5; Tiljander et al. 2003) and not in the central/eastern sites, it appears that the LIA had spatially different characteristics in different parts of Finland. In addition, the two-phased LIA with a warm episode at ~1650 CE has been reconstructed from western Scandinavia (southern Norway) (Zawiska et al. 2016) suggesting that the short-lived warm period may be attenuated along the continental-ity gradient towards east.

Due to the lower temporal resolution in the 2000-year sediment profiles, the detailed timing in the initiation of the recent warming cannot be resolved similarly as from the decadal-scale 700-year profiles. However, all the centennial-scale records show a progressive temperature increase

from ~1850 CE onwards, although in the northern site, this period is represented by a single sample. Similar to the decadal-scale reconstructions, the present inferred-temperatures in all sites represent record-high values. Although substantial divergences exist during certain periods, our timeseries display a reasonably coherent picture of major climatic episodes: the MCA, LIA and recent warming, as also evidenced previously from hemispheric temperature records (Esper et al. 2005).

#### 4.4 How warm/cold were the MCA and LIA?

There exists a relatively uniform signal of the MCA in Northern Hemisphere that indicate that it was not as warm as the present climate, however, with some regional differences (Crowley and Lowery 2000; Bradley et al. 2003). Our decadal reconstruction only capture the ending of the MCA (showing lower than present-day temperatures, Fig. 4) but the centennial-scale reconstructions systematically show temperatures, which are clearly lower than present (Fig. 5). In the southern site, the maximum MCA temperatures remain ~0.5 °C lower than present and on average the MCA was almost 1 °C cooler than present, these estimations being close to what has been found from the Northern Hemisphere in general (Jansen et al. 2007). The difference between the MCA and present-day conditions was rather similar at the northern site, but in the central site the difference was larger, as the temperatures were on average 1.5 °C lower from the present temperature increase. These differences may be partly related to greater continentality towards the east dictated by the large Eurasian landmass in connection with the major shifts in the NAO index (Trouet et al. 2009).

Compared to the MCA, the contrast between the present day temperatures and the LIA was more drastic. Depending on the resolution and temporal scale of the reconstructions, they all showed a ~2–3 °C difference in the maximum values and a ~1.5–2 °C difference in the mean values, the central sites having the largest temperature difference. The Northern Hemispheric temperature difference between the LIA and the present has generally been ~0.7–1.5 °C (Moberg et al. 2005; Jansen et al. 2007) suggesting that the temperature changes are amplified in the current study area. In contrast to the MCA, which triggered an expansion in human population of Finland (Kepsu 2001; Lindkvist 2002), the LIA led to agricultural depression in Finland (Luoto et al. 2009) and decline in population due to the serious famine caused by undernourishment and diseases (Rantanen and Kuvaja 1994; Wilmi 2003). The most severe period of famine and death, around 1700 CE, is synchronous with the changes in the temperature reconstruction, especially in Southern Finland (Figs. 5, 6). These results reflect the prominent connections between long-term air

temperature changes, yield success and human population dynamics in Northern Europe.

The spatiotemporal patterns of the LIA have significant differences in our study site (Fig. 6) and confirm climate information derived from historical writings based on yield success and human population dynamics (Rantanen and Kuvaja 1994; Wilmi 2003; Holopainen and Helama 2009). In south, the LIA was divided into two cooling periods during the sixteenth and seventeenth centuries, whereas in the Central/Eastern Finland, the cool period began immediately after the MCA, and lasted longer, until the onset of the twentieth century warming. In the north, the LIA was delayed compared to south and central sites but it ended at the same time as in the central site at the beginning of the twentieth century warming. These differing temperature trends suggest that spatial patterns in external forcing play prominent role between our study sites.

#### 4.5 External forcing

In common with a previous study from Finland covering the most recent centuries (Holopainen et al. 2009), the reconstructed temperatures generally do not mimic specific forcing alone, but they give guidance on the characteristics of local climate variability in Northern Europe. The influence of external forcing on climate of the southern and central sites appear to be complex at the decadal scale, but in the northern site the temperature changes are closely linked to the NAO (Fig. 4). However, solar activity appears to be synchronous with the temperature changes at the centennial scale at all the sites (Fig. 5).

A previous study from Eastern Finland suggested a strong climate response to the NAO with cold LIA characterized by wet summers and dry winters (negative NAO index phase) and warm MCA with dry summers and wet winters (positive NAO index phase) (Luoto and Helama 2010). During the past 100 years the NAO index has varied considerably, but it has remained in a more positive phase during the late twentieth century compared to the LIA (Marshall et al. 2001). The recent variability is reflected at the decadal scale in the northern site and some of this fluctuation is also captured by the temperature signal in the southern site (Fig. 4). However, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations (Mitchell et al. 2001) and the share of volcanic and solar irradiance forcing on Northern Hemispheric temperatures compared to other forcing mechanisms has been clearly diminishing (Jansen et al. 2007).

All the present temperature records at the centennial-scale show connection with the NAO. At the decadal-scale, the NAO is synchronous mostly in the northern site during the major climate events of the CE implying spatial



variability in response to forcing at different temporal resolutions. Though the influence of the NAO is evident on long-term climate development of Northern Europe, solar forcing is likely to be proportionately more important before the twentieth century (Stott et al. 2003). In particular, during the LIA there is a potential strong amplification of the response to the solar forcing (Goosse and Renssen 2004). Furthermore, the LIA signal can be attributed to both volcanic and solar forcing (Shindell et al. 2001). It has been suggested that the contrast between the MCA and the LIA was due to the coincidence of solar activity minima with an increased number of volcanic events during the LIA (Wanner et al. 2008). For example, the temperature decrease in the northern sites (Figs. 4, 5) at the end of LIA, shortly after 1800 CE is synchronous with volcanic eruptions with global imprint (Briffa et al. 1998; Gao et al. 2007). There are clear associations between solar forcing and temperature dynamics in all the current sites at the decadal-scale but at the centennial-scale these connection become even more synchronized. Thus, there are indications of a correspondence between the temperature variability in different parts of Finland and NAO, as well as with solar forcing, that has been also suggested by Holopainen et al. (2009). Since the present results suggest differences not only in the climate development but in the influence of processes behind them, further investigations are needed for better understanding of climate change and its key processes and forcing mechanisms at different spatial and temporal scales.

## 5 Conclusions

Validation of the applied temperature calibration method in the high-resolution sediment core indicated that the chironomid-inferred and instrumentally measured summer air temperatures correlate closely with each other. This result provided the opportunity for reliable long-term reconstructions from the selected downcore sites. Temperature reconstructions at the decadal temporal scale showed some spatial differences in timing of the LIA and the initiation of recent climate warming between southern, central and northern sites. In particular, the longer extent of LIA and the subsequent later onset of the anthropogenic warming in the central and northern sites compared to south were clearly evidenced by our data. The MCA and LIA were distinguished in all of the centennial-scale reconstructions, but there were also spatial differences in their timing, such as earlier timing of the MCA in Central Finland together with the shorter LIA in the south. Complex association were found in the influence of external forcing on climate of the southern and central sites at the decadal scale, but the temperature changes in the northern site were strongly linked

with the NAO. At the centennial scale, solar intensity was synchronous with the temperature changes at all the sites. The results of the present study provide new information on spatial differences in timing of major climate events of the past 2000 years in Northern Europe. We were also able to link the air temperature changes with external forcings enabling greater understanding of large-scale processes and mechanisms behind the long-term climate trends. This knowledge is essential for better and holistic prediction of the development and impacts the ongoing climate change.

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