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Late Holocene precipitation and temperature changes in Northern Europe linked with North Atlantic forcing

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ABSTRACT: Long-term paleoclimatic records are needed for understanding natural variability in the context of climate change. Two lake sediment cores were collected from eastern Finland from sites considered sensitive for precipitation and temperature, respectively, over the last ~3000 yr. The paleoclimatic reconstructions based on fossil Chironomidae (Insecta: Diptera) assemblages were considered against a North Atlantic Oscillation (NAO) reconstruction to disentangle possible forcing mechanisms. Generally low effective precipitation was reconstructed between ~3000 and 1500 cal yr BP (calibrated years before present). A distinct stream flow event occurred between ~2400 and 2200 cal yr BP, and the highest effective precipitation occurred ~1300 cal yr BP. The Medieval Climate Anomaly (MCA) between ~1200 and 800 cal yr BP was dry, but the Little Ice Age (LIA) between ~700 and 200 cal yr BP had fluctuating precipitation. The temperature reconstruction depicted a late Holocene cooling trend, which ended at ~1300 cal yr BP when the warm MCA began. The MCA was followed by the cold LIA and the last 100 yr have been characterized by rapid warming. Present temperatures are higher than during any time period of the late Holocene. A general trend of positive NAO mode with elevated summer temperatures and dry hydroclimatic conditions prevailed during the MCA and a negative mode with reduced temperatures during the LIA. However, the NAO–hydroclimate relationship over eastern Scandinavia was not straightforward during the LIA, which varied in moisture dynamics. The records from this present study provide a unique climate archive from the crossing point of southern and northern and eastern and western air masses.

KEY WORDS: Chironomidae · Climate change · Eastern Finland · North Atlantic Oscillation · Paleoclimatology

1. INTRODUCTION

Understanding large-scale and long-term climate behavior necessitates spatially distributed proxy data (PAGES 2k Consortium 2013). In the absence of direct millennial-scale climate data, paleoclimatic archives, such as those stored in lake sediments, can be used to reconstruct past climate conditions. There is a special need for precipitation data, since there has been a strong paleoclimatic focus on temperature reconstructions.

The North Atlantic has a direct influence on the climate of Northern Europe and Scandinavia through the upper troposphere jet stream as the strong westerly atmospheric circulation provides heat and moisture transport from the Gulf Stream. Another significant feature, especially in the climate of Scandinavia, is related to continentality that increases towards the

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*Corresponding author: tomi.luoto@helsinki.fi east. Therefore, paleoclimate archives from lake sediments in the boreal zone are needed to better understand the connections between regional climate and marine–continental regimes. Boreal lakes are particularly sensitive to climate changes due to their northern location and associated vulnerability to changes in ice-covered and snow-covered periods (Keller 2007, Holmberg et al. 2014).

In the North Atlantic sector, the natural climate changes originating from the Atlantic Ocean drive multi-decadal variations (Visbeck et al. 2001, Sutton & Hodson 2005). The large-scale climatic patterns, teleconnections or preferred modes of low-frequency (or long time scale) variability, explain a major part of the variability in atmospheric circulation. These recurring and persistent features of the atmospheric system are large-scale patterns of pressure and circulation anomalies that reflect changes in the atmospheric wave and jet stream patterns. The most significant pattern is the North Atlantic Oscillation (NAO), which consists of a north–south dipole of anomalies, with one center located over Greenland and the other center of opposite sign spanning the mid-latitudes of the North Atlantic. The positive NAO phase reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic and Western Europe, whereas the negative phase reflects an opposite pattern (Visbeck et al. 2001). There exists a modern (decadal) positive correlation between NAO and temperature during both winter and summer, whereas the correlation between NAO and precipitation is positive during winter and negative during summer in eastern Scandinavia (Luoto & Helama 2010). This phenomenon also appears to have prevailed during a major part of the past millennium (Helama et al. 2009, Luoto & Helama 2010, Luoto et al. 2013).

In this study, we examine 2 lake sediment cores from eastern Finland using paleolimnological methods. The study sites are considered to be sensitive to precipitation (a seepage lake) and temperature (a drainage lake) enabling their use for specific paleoclimatic inferences. Calibration models of water depth (effective precipitation) and mean July air temperature (TJul) based on fossil Chironomidae (Insecta: Diptera) were applied for quantitative paleoclimate reconstructions. Lotic insect remains were used for evidence of stream flow events. Chironomid growth and development is directly influenced by surrounding temperature throughout their life cycle (Eggermont & Heiri 2012). However, the influence of water depth on benthic chironomid larvae is mostly indirect and mediated through changes in habitat availability and depth-related factors, such as limnological conditions and predation pressure (Luoto 2010). The relative significance of temperature and depth in controlling distribution and abundance of chironomid communities depends largely on the lake type (e.g. drainage versus seepage lakes). Thus, fossil chironomid analysis has been used to quantitatively reconstruct both temperature (Heiri & Lotter 2005, Luoto & Nevalainen 2013a) and water depth (Korhola et al. 2000, Nazarova et al. 2011).

The paleoclimatic reconstructions covering the late Holocene (the past ~3000 yr), are compared with an NAO reconstruction for support of possible forcing mechanisms behind the climate trends. Reconciling the modern NAO–climate correlations (Hurrell & van Loon 1997) and reconstructions of the NAO (Trouet et al. 2009) with our paleoclimate evidence, the results of our study can be significant in revealing differences and trends in precipitation and temperature dynamics in the climatically sensitive eastern Scandinavia, and in unraveling the driving mechanisms and the possible role of the NAO behind these changes.

2. REGIONAL SETTING

The 2 study lakes are located in the north boreal vegetation zone in Kuhmo, eastern Finland, within ~2.7 km of each other (Fig. 1). The mean air TJul at the lakes is 15.2°C and the annual precipitation in the area is 600 to 650 mm with the rainiest months occurring during the summer (Luoto & Helama 2010). Despite both sites being pristine, adjacent and having similar altitude and climate conditions, the lakes are fundamentally different in their hydrological settings making them suitable for different paleolimnological inferences.

Kylmänlampi (64° 18′ N, 30° 15′ E; 192.7 m a.s.l.) is a small clear-water kettle lake situated in the Kylmänsärkät esker formation. The ~3 ha catchment area with steep gravel fringes is covered by coniferous trees (*Pinus sylvestris* and *Picea abies*). The rounded lake is deep in relation to its size (maximum depth of 16.4 m). Kylmänlampi is a precipitation- and groundwater-dominated closed system that makes it suitable for lake level reconstructions and inferences of effective moisture fluctuations. The location of the basin in a deep glaciofluvial gravel depression (10 to 20 m difference between the water surface and fringe margins) means that there is no risk of over-

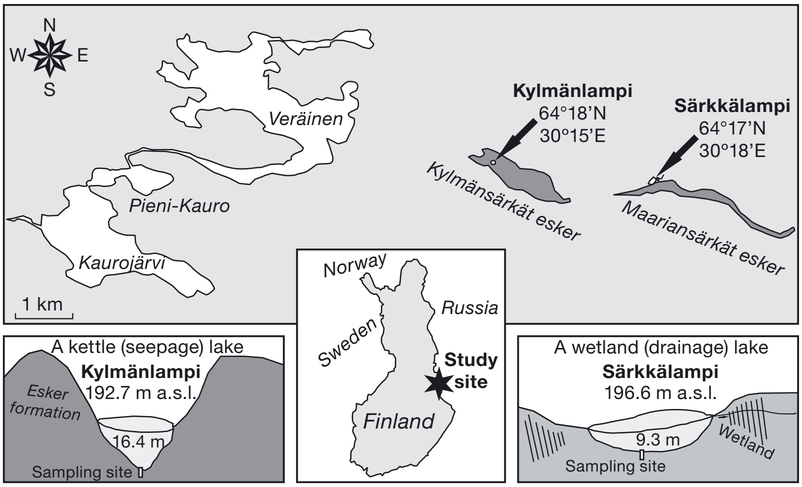

Fig. 1. Location of the study site in eastern Finland. The 2 study lakes, Kylmänlampi and Särkkälampi, are located close to Pieni-Kauro for which paleoclimatological data is also available. Lake areas are marked in white and the esker formations in dark grey. Kylmänlampi is a groundwater- and precipitation-fed deep kettle lake and Särkkälampi is a shallower well-drained peatland lake at approximately the same altitude. In the lower panel figures, the lake surface areas are drawn on the catchment cross-sections to illustrate their shape. The sediment cores were collected from the deep basins

Table 1. Characteristics of the study lakes: Kylmänlampi and Särkkälampi, Finland. All limnological measurements were performed from epilimnetic water sampled in early October 2013

	Kylmänlampi	Särkkälampi
Location	64° 18′ N, 30° 15′ E	64° 17′ N, 30° 18′ E
Altitude (m a.s.l.)	192.7	196.6
Catchment area (ha)	3	10
Maximum depth (m)	16.4	9.3
pH	5.2	6.4
Total organic carbon (mg C l^{-1})	2.4	5.7
Dissolved organic carbon (mg C l^{-1})	2.2	5.3
Dissolved oxygen (mg l^{-1})	8.0	7.6

flow, which would cause failure of a lake level reconstruction. As a landlocked water body, the principal source of water is precipitation, supplemented by groundwater from the immediate drainage area at the esker formation; hence seepage lakes such as Kylmänlampi commonly reflect groundwater levels and rainfall patterns (Mason et al. 1994). Kylmänsärkät and Kylmänlampi are located in a protected nature reserve (Iso-Palosen ja Maariansärkkien luonnonsuojelualue).

Särkkälampi (64° 17′ N, 30° 18′ E; 196.6 m a.s.l.) is a small dystrophic (polyhumic) bog lake with a maximum depth of 9.3 m, situated in the Särkkäsuo wetland next to the Maariansärkät esker formation. In addition to the immediate mire, the ~10 ha catchment area is partly covered by coniferous trees. The surface-water dominated system is well-drained via an outlet in its eastern side, which makes it less sensitive to lake level changes. Furthermore, the Särkkäsuo bog drains efficiently through the River Viiksimonjoki, making Särkkälampi more suitable for temperature, rather than lake level, reconstructions. Limnological characteristics of the lakes are given in Table 1.

3. MATERIALS AND METHODS

3.1. Sediment profiles

Sediment profiles were collected using the HTH Sediment Corer (Pylonex; Renberg & Hansson 2008), a gravity corer with a tube diameter of 70 mm and length of 50 cm. The sampling was performed from a rubber boat in early October 2013 at the center of the lakes. The sediment samples were taken from a depth of 15.9 m in Kylmänlampi and 8.9 m in Särkkälampi. Both sediment cores (subsampled in the field at 1-cm intervals) consisted of visually homogenous macrophyte-rich sediment. Living aquatic mosses were present at the core tops, indicating that the surface of both profiles represents the present.

3.2. Analyses

Loss on ignition (LOI) was performed to assess the sediment composition (organic content) from wet sediment using a sample size of approx. 3 g. The samples were dried at 105°C for 12 h and heated in an oven at 550°C for 2 h (Heiri et al. 2001). Since LOI is closely related to water depth (Luoto & Nevalainen 2013b), it was also used as a proxy for lake level changes in Kylmänlampi. The cores were dated using the accelerator mass spectrometry (AMS) ^{14}C method to provide a chronology. Four macrofossils used in the ^{14}C dating were isolated from the sediment core during sub-sampling. The macrofossils comprising 3 pine needles and a bark sample were analyzed at the Beta Analytic Radiocarbon Dating Laboratory, Miami, Florida, USA. The calibration of the dates (2 sigma calibrated results) was performed using the INTCAL13 database (Reimer et al. 2013).

Subsamples for fossil midge analysis were prepared using standard methods (Brooks et al. 2007). The wet sediment was gently sieved through a 100 µm mesh and the residue was examined using a Bogorov counting chamber under a stereomicroscope (32–40× magnification). Larval head capsules were extracted with fine forceps and mounted permanently with Euparal on microscope slides. Faunal identification was performed under a light microscope at 400× magnification. The minimum chironomid head capsule number per sample was set to 50. Identification of the chironomids was based on Brooks et al. (2007).

The water depth reconstruction of Kylmänlampi was performed using the expanded Finnish chironomid-based calibration model (weighted averaging-partial least squares, WA-PLS) (Luoto 2009a, Luoto et al. 2010). The 68-lake model has a water depth gradient between 0.7 and 18.0 m and includes 84 chironomid taxa. The transfer function has a cross-validated coefficient of determination (r^2_{jack}) of 0.68, a root mean squared error of prediction (RMSEP) of 0.78 m and a maximum bias of 2.02 m. The chironomid-based mean air TJul reconstructions used the Finnish calibration model (WA-PLS). The temperature gradient in the training set varies from 11.3 to 17.0°C and includes subarctic and boreal lakes (60 to 70° N). The model includes 77 lakes and 72 taxa having an r^2_{jack} of 0.78, an RMSEP of 0.72°C and a maximum bias of 0.79°C (Luoto 2009b, Luoto et al. 2009). Based on lake selection criteria, there is no correlation between temperature and depth in either of the training sets. Sample-specific errors (eSEP) were estimated using bootstrapping cross-validation (999 iterations).

All statistical analyses were run using relative taxa abundances using square-root transformation and down-weighting of rare taxa. Principal component analysis (PCA) was used to indicate the primary direction of community variance in the sediment profile (PCA axis 1 scores). The fossil samples were tested for their modern analogues in the calibration set by applying the modern analogue technique (MAT) and squared chord distances to assess the suitability of the training data for the core samples. Taxon response models were constructed using generalized linear models (GLM) to identify significant relationships between the core taxa and environmental variables of interest (water depth or temperature) in the calibration data. The GLMs were set to a quadratic degree and Poisson distribution. The topmost inferred values were compared with the measured modern conditions to assess how realistic the reconstructions of the surface samples are.

The precipitation and temperature reconstructions from Kylmänlampi and Särkkälampi were compared with ~1500 yr paleolimnological reconstructions of mean air TJul and streamflow (based on chironomids and lotic insects) (Luoto & Helama 2010, Luoto et al. 2013) from Lake Pieni-Kauro (and Saavanjoki River) located ~8 km from Särkkälampi and ~5 km from Kylmänlampi (Fig. 1). A ~1000 yr winter NAO reconstruction based on a speleothem precipitation proxy from Scotland and a tree-ring-based drought proxy from Morocco (Trouet et al. 2009) were used to assess the possible influence of the NAO as a driver for the reconstructed precipitation and temperature changes in eastern Scandinavia. The NAO data (Trouet et al. 2009) were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (www.ncdc.noaa.gov).

4. RESULTS

The lowermost sample at 27 cm in Lake Kylmänlampi indicated an AMS ^{14}C age of 2780 to 2740 cal yr BP. The sample at 20 cm was too small and did not contain enough carbon for reliable age determination and was therefore rejected from the age-depth model. For Särkkälampi, the basal age at the bottom of the core (35 cm) was estimated to be 3560 to 3400 cal yr BP. In Särkkälampi, a dated sample at 16 cm showed an age of 2205 to 2115 cal yr BP. The dating results are listed in Table 2. These results suggest a similar annual accumulation rate of 0.1 mm in both cores, implying that the age–depth models

Table 2. Accelerator mass spectrometry (AMS) ^{14}C dates from terrestrial plant macrofossils in the 2 sediment cores from the 2 lakes, Kylmänlampi (KL) and Särkkälampi (SL), Finland. Sample KL 20 cm did not contain enough carbon for reliable age determination and was therefore rejected from the age-depth model

Sample	Code	Material	Measured ^{14}C age	2 sigma calibration
KL 20 cm	396888	Pine needle	3300 ± 30 yr BP	Cal yr BP 3515 to 3390
KL 27 cm	396889	Pine needle	2660 ± 30 yr BP	Cal yr BP 2780 to 2740
SL 16 cm	396890	Pine needle	2210 ± 30 yr BP	Cal yr BP 2205 to 2115
SL 35 cm	396891	Bark	3290 ± 30 yr BP	Cal yr BP 3560 to 3400

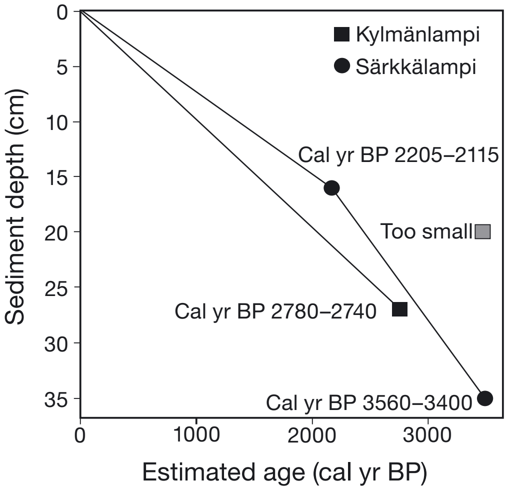

Fig. 2. Accelerator mass spectrometry (AMS) ^{14}C dates from terrestrial plant macrofossils in sediment cores from Lakes Kylmänlampi (n = 1) and Särkkälampi (n = 2), Finland, and the applied linear age–depth model. The average sedimentation rate of the cores is 0.01 mm yr^{-1}. The sediment sample at 20 cm from Kylmänlampi did not have enough carbon for a reliable age estimate (designated as 'too small') and was therefore rejected from the model

(Fig. 2) are realistic. However, due to the low number of macrofossils (and subsequently reduced number of dates) and the unsuccessful dating of one ^{14}C sample, the chronologies should be interpreted as tentative.

The Kylmänlampi core, with 19 chironomid taxa present, was dominated throughout by *Sergentia coracina*-type with a minimum of 53% (~400 cal yr BP) and maximum of 92% (~1200 cal yr BP) (Fig. 3). In addition, *Ablabesmyia monilis*-type (0–26%) and *Psectrocladius sordidellus*-type (0–21%) were common. *A. monilis*-type was especially abundant between ~2000 and 1800 cal yr BP and *P. sordidellus*-type between ~500 and 400 cal yr BP. *P.* (*M.*) *septentrionalis*-type appeared in the stratigraphy during the past ~600 yr.

The Särkkälampi core contained 46 chironomid taxa. The most abundant taxon between ~3500 and 2400 was *Propsilocerus jacuticus*-type (4–36%). *Chironomus anthracinus*-type (3–29%) was also abundant (Fig. 4). *Procladius* (5–30%) and *Psectrocladius sordidellus*-type were the most abundant taxa between ~2400 and 2000 cal yr BP. *S. coracina*-type (10–39%) and *C. anthracinus*-type (3–31%) increased from ~1800 cal yr BP onwards, while *P. jacuticus*-type disappeared from the stratigraphy. *C. anthracinus*-type (20%) and *A. monilis*-type (8–20%) were most abundant during the last 200 yr.

On average, 95% of the fossil taxa in Kylmänlampi had a significant relationship with water depth in the

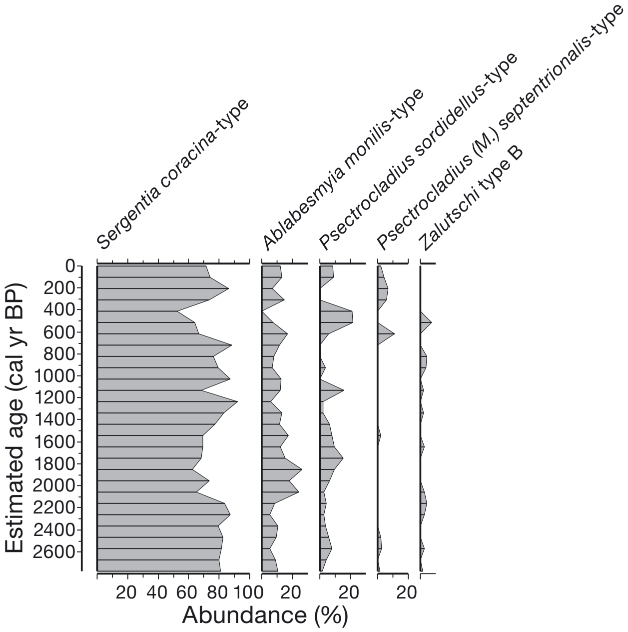

Fig. 3. Relative abundance (%) of the most common fossil chironomid taxa in Kylmänlampi, a groundwater- and precipitation-fed kettle lake in Finland

calibration data (assessed by the GLMs) and 80% of the fossil taxa in Särkkälämpi were significantly related to temperature (Fig. 5). Only the sample at ~2100 cal yr BP in Särkkälampi had a markedly reduced number of temperature indicator taxa present (33%). In Särkkälampi, the samples between ~2400 and 2200 cal yr BP had poor modern analogues (Fig. 5) due to the presence of *Stilocladius*, which is absent in the training set. The reconstructed water depth in Kylmänlampi and temperature in Särkkälampi showed good correspondence with the PCA axis 1 scores in the respective lakes.

The reconstructed lake levels in Kylmänlampi varied between 10.9 (~400 cal yr BP) and 22.8 m (~1000 cal yr BP). At ~2700 cal yr BP the lake level was lower, increasing during the period between 2600 and 2200 cal yr BP (Fig. 6). This high lake level phase was accompanied by a simultaneous increase of lotic insects (e.g. mayflies and caddisflies) in Särkkälampi. The lake level was again lower between ~1800 and 1500 cal yr BP and increased between 1400 and 600 cal yr BP. A short-lived dry phase occurred between 500 and 400 cal yr BP, after which the lake level remained slightly elevated until the present. The reconstructed water depth for the surface sample was 17.7 m, overestimating the measured value by 1.8 m, which is over the model's RMSEP of 0.78 m and the eSEP of 1.2 m.

The reconstructed temperatures in Särkkälampi varied between 13.7 (~700 cal yr BP) and 16.1°C (the present, Fig. 6). A late Holocene cooling trend oc-

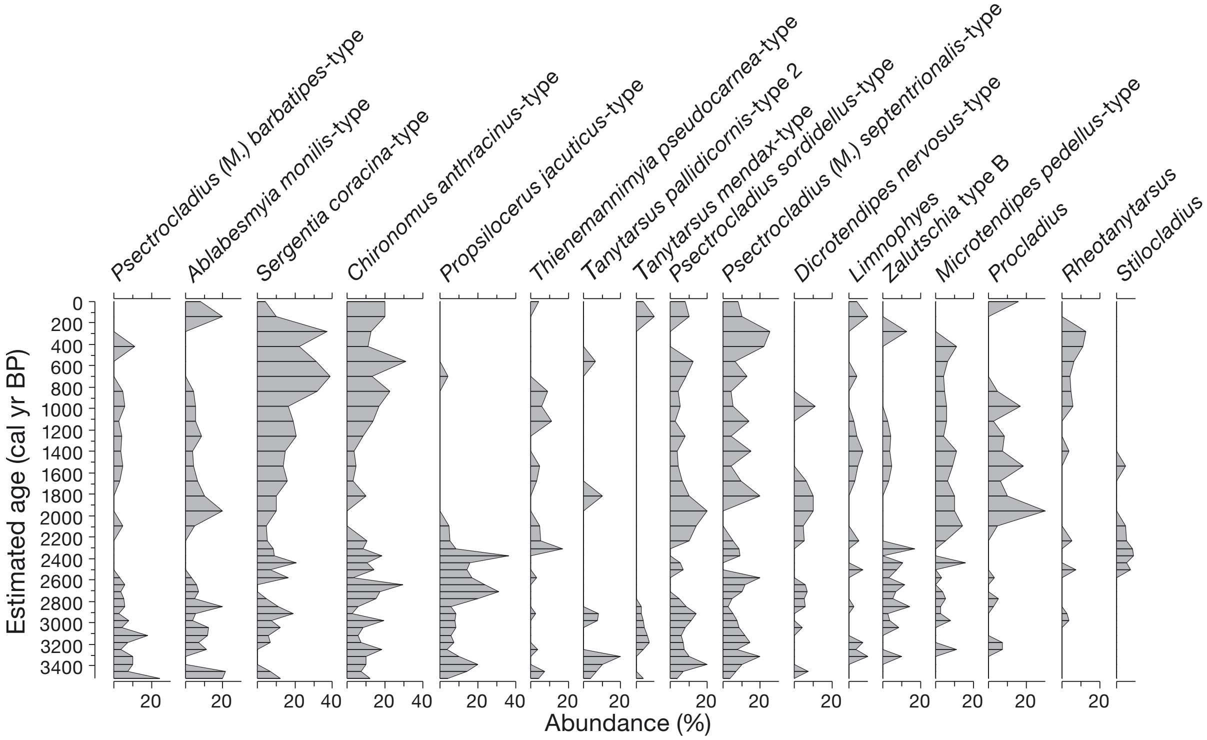

Fig. 4. Relative abundance (%) of the most common fossil chironomid taxa in Särkkälampi, a shallow well-drained peatland lake in Finland

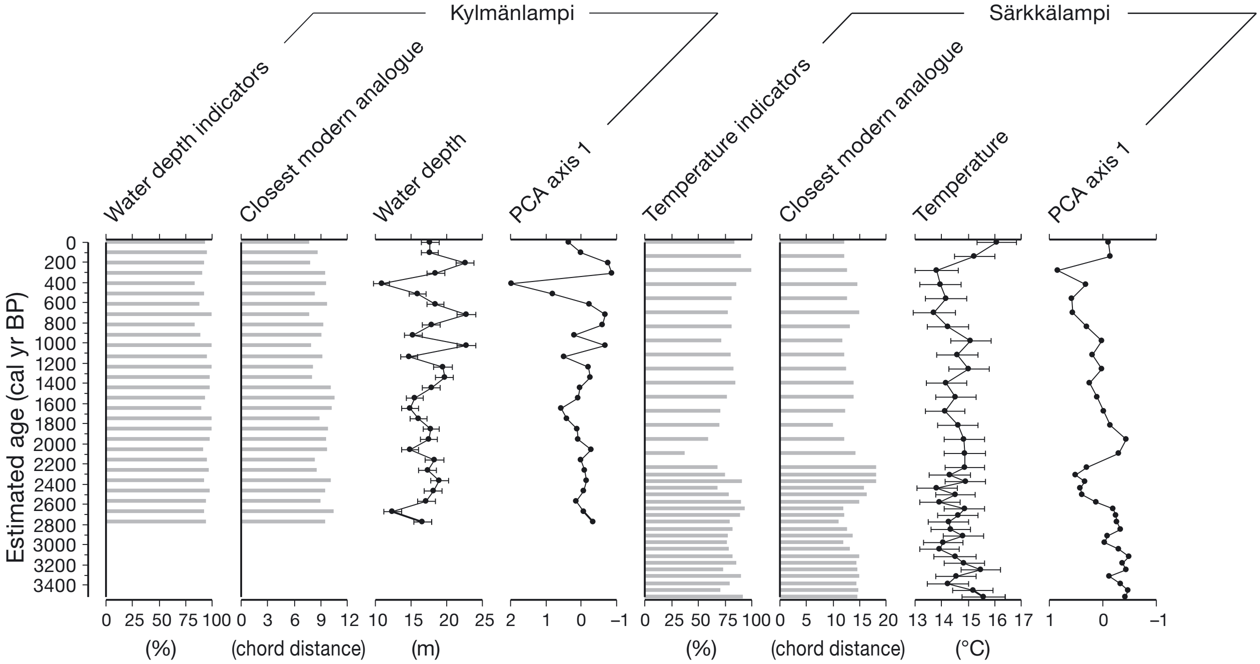

Fig. 5. Reconstructions of climate at Lakes Kylmänlampi and Särkkälampi, Finland, based on relative abundance of indicator taxa (Luoto 2011), closest modern analogues, sample-specific error estimates for the reconstructed variables and PCA axis 1 scores (reversed). The indicator taxa in the calibration sets were assessed using generalized linear models (GLM), modern analogues were assessed using squared chord distances in the modern analogue technique (MAT) and the error estimates for the inferences were assessed using bootstrapping cross-validation (999 iterations)

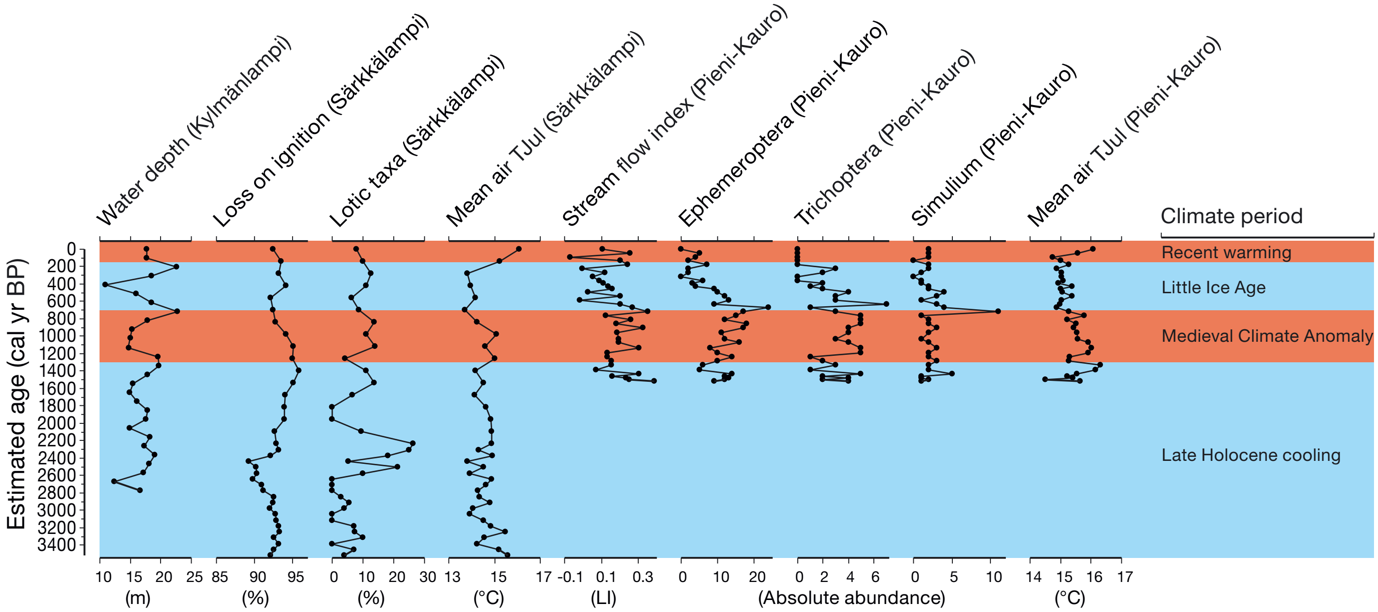

Fig. 6. Precipitation and temperature records over the last 1000 yr from the study region in eastern Finland. Proxies for precipitation include loss on ignition (lake depth in Särkkälampi), chironomid-inferred water depth (Kylmänlampi), proportion of lotic taxa (stream influence in Särkkälampi) and stream flow indicating aquatic insect proxies from the adjacent Pieni-Kauro. The chironomid-based mean July air temperature (TJul) reconstruction from Särkkälampi is compared with a similar reconstruction from Lake Pieni-Kauro (Luoto & Helama 2010). Cool climate phases are marked in blue and warm in red

curred in the record between ~3500 and 1500 cal yr BP. Temperatures increased between 1300 and 1000 cal yr BP, and decreased between 700 and 300 cal yr BP. The highest temperature in the sediment record is reconstructed to the surface sample representing the present. The reconstructed value for the surface sample was 16.1°C, overestimating the observed temperature by 0.9°C, which is slightly over the model's RMSEP of 0.72°C and the eSEP of 0.74°C.

5. DISCUSSION

5.1. Assessment of the chironomid-based reconstructions

The study sites (Fig. 1) were selected so that they represent a closed seepage system that is sensitive to changes in precipitation (a deep kettle lake with small surface area) and an open drainage system that is not significantly influenced by atmospheric moisture changes, but rather changes in air temperature. Careful selection of the study sites was especially important because interaction between temperature and lake morphometry may confound chironomid-based paleoclimate inferences from lake sedimentary records (Eggermont & Heiri 2012, Chen et al. 2014). The sediment record of Kylmänlampi was dominated throughout by the deep water taxon *Sergentia coracina*-type (Luoto 2012a, Jyväsjärvi et al. 2013), although it experienced changes in its relative abundance (Fig. 3). Since *S. coracina*-type is significantly related to water depth in the applied training set, the changes in its abundance in the Kylmänlampi core can be related to changes in lake depth. It is noteworthy that also the rest of the taxa, including *Psectrocladius sordidellus*-type and *Ablabesmyia monilis*-type, were significantly related to water depth indicators (Fig. 5), increasing the plausibility of the water depth reconstruction. Furthermore, the assemblages had close modern analogues, and the PCA axis 1 scores (mostly driven by *S. coracina*-type) showed close similarity with the reconstructed values, which can be considered to indicate reliability of the transfer function used (Laird et al. 2011, Rantala et al. 2015).

Compared to Kylmänlampi, which has reduced habitat availability due to its bathymetry and limnology (Fig. 1), Särkkälampi had more diverse and abundant chironomid fauna (Fig. 4). Most of the core taxa had significant relationships with temperature in the calibration set used, and the PCA axis 1 scores indicated that the primary direction of community variance had trends similar to those of the reconstructed temperature values (Fig. 5). However, in the sample at ~2100 cal yr Bp, <50% of the taxa were temperature indicators. In addition, 3 samples between ~2400 and 2200 cal yr BP did not have close modern analogues, probably due to the presence of a stream taxon *Stilocladius* (Brooks et al. 2007), which is absent in the lacustrine-based training set we used. Therefore, the temperature reconstruction between ~2400 and 2100 cal yr BP has reduced reliability compared to the rest of the core, although this is not seen from the sample-specific error estimates (Fig. 5).

5.2. Effective precipitation and air temperature reconstructions

According to the temperature reconstruction from Särkkälampi (Fig. 6), the climate generally cooled from the beginning of the sediment record from ~3500 to 3000 cal yr BP, and the temperature remained low until 1400 cal yr BP. This time period corresponds with the late Holocene cooling period, which has been previously described from Finland (Tiljander et al. 2003, Ojala et al. 2008, Engels et al. 2014). More specifically, the warm phase in the initial part of the present record corresponds to the ~4000/3000 cal yr BP warm event in the middle of the late Holocene cooling event previously described from northern Finland (Korhola et al. 2002, Salonen et al. 2013, Luoto et al. 2014).

The lake level reconstruction from Kylmänlampi extends back to ~2800 cal yr BP; for Särkkälampi, the dates extend as far back as ~3500 cal yr BP. In Särkkälampi, the LOI results, which are generally dependent on water depth (Luoto 2012b), suggest an elevated lake level between ~3500 and 2800 cal yr BP (Fig. 6). Therefore, the 4000/3000 cal yr BP climate event in Northern Scandinavia appears to have been warm and moist, though the LOI results may also be influenced by factors such as changes in productivity and catchment erosion. A dry period occurred between ~2800 and 2500 cal yr BP, indicated by the LOI results from Särkkälampi and the lake level reconstruction from Kylmänlampi. In addition, lotic taxa were absent from the Särkkälampi record during this phase, suggesting that stream contribution was insignificant at the time. However, between ~2500 and 2200 cal yr BP the relative abundance of lotic taxa such as *Stilocladius* (Fig. 4) increased to the highest values on record, indicating increasing streamflow. The increased surface runoff during this time is supported by the lake level reconstruction from Kylmänlampi. There is some mismatch between the different precipitation-related proxies (LOI, water depth reconstruction, lotic taxa) during ~2000 and 1500 cal yr BP that makes hydroclimatic interpretations of the period difficult. A previous study from Finnish Lapland has shown low lake levels at this time (Luoto & Sarmaja-Korjonen 2011) that are consistent with the lake level reconstruction from Kylmänlampi. Despite the differences between the proxies in this study, there was a common increase in precipitation based on all the proxies that culminate at ~1400 cal yr BP.

Between ~1200 and 1000 cal yr BP, the lake level reconstruction from Kylmänlampi shows low water depth, while the reconstruction from Särkkälampi indicates increased temperatures. These changes are consistent with the Medieval Climate Anomaly (MCA) and provide evidence for the interpretation that the MCA was warm and dry in eastern Finland (Helama et al. 2009, Luoto & Helama 2010; our Fig. 6). It has also been shown that the dry condition at the initiation of the MCA was followed by a progressive increase in precipitation in the area (Nevalainen et al. 2013) culminating with higher lake levels from ~800 to 700 cal yr BP, which is similar to the present reconstruction. The high effective precipitation from ~800 to 700 cal yr BP is further evidenced by the streamflow data (high relative abundance of lotic taxa) from the adjacent Lake Pieni-Kauro (Luoto et al. 2013; our Fig. 6).

The distinct changes in climate conditions from ~800 to 700 cal yr BP coincide with the transition between the MCA and the Little Ice Age (LIA). Although the term LIA is fairly ambiguous due to its spatiotemporal differences and variation in magnitude (Matthews & Briffa 2005), a harsh climate period is well defined between 700 and 100 yr ago in Finnish historical writings (Melander & Melander 1924, Wilmi 2003). Some records suggest increased precipitation from ~500 to 400 cal yr BP (Helama et al. 2009, Nevalainen et al. 2013), but together with the streamflow data from Pieni-Kauro the present evidence imply that the moistest period occurred between ~800 and 700 cal yr BP at the initiation of the LIA, and a second wet period between ~300 and 200 cal yr BP at the end of the LIA. The LIA climate has been shown to be bimodal in its trends in southern Finland (Luoto et al. 2008), but the temperature reconstructions from Särkkälampi and Pieni-Kauro indicate persistently cold summer temperatures between 700 and 200 cal yr BP in the eastern part of the country. Generally, the present paleoclimatic evidence agrees with the previous indications that the LIA was cold and wet and lasted in eastern Scandinavia from ~700 to 100 cal yr BP (Luoto & Helama 2010).

The precipitation reconstructions for the past 100 yr suggest a slightly decreasing trend (Fig. 6), which is consistent with the tree-ring-based precipitation (Helama et al. 2009) and Cladocera-based lake level (Nevalainen et al. 2013) reconstructions from eastern Finland. The temperature reconstruction from Särkkälampi and also the previous reconstruction from Pieni-Kauro show a rapid warming during the past century. It should be noted though, that the temperature of the topmost sample was overestimated by 0.9°C when compared with the observed value.

When comparing the inferred mean air TJul value for the surface sample with the temperatures inferred for the LIA, there is a ~2°C difference, with a maximum of 2.4°C. This difference is consistent with a previous reconstruction from southern Finland, which also showed temperatures ~2°C cooler than present (Luoto 2013). In addition, the difference between the present vs. LIA temperatures in Europe is generally 2 to 3°C (Büntgen & Hellmann 2014). Compared to the MCA, the present day temperatures represent ~1°C higher values. This agrees with the finding that the MCA displayed regional-level warmth that matches or exceeds that of the past decade in our study region, but which globally falls well below recent levels (Mann et al. 2009).

5.3. Synoptic paleoclimate context

In the past millennia, climate trends have been forced by factors such as volcanic and solar activity, but since the 19th century and especially from the 20th century onwards, greenhouse gases have clearly become the most important climate-forcing mechanism (PAGES 2k Consortium 2013). In Northern Europe, the natural climatic changes originate from the Atlantic Ocean and have driven multidecadal variations over the past centuries (Sutton & Hodson 2005). Furthermore, there is a significant influence of the El Niño-Southern Oscillation (ENSO) on the short- and long-term climatic fluctuations in Europe (Brönnimann et al. 2004, 2007, Helama et al. 2009). The NAO, which is closely related to the Arctic Oscillation (AO), is a major mode of atmospheric variability in the Northern Hemisphere, particularly in winter. The proximity of the North Atlantic to the present study region justifies the interpretation of the results in the context of the NAO (Trigo et al. 2002). Unfortunately, there is limited knowledge on the long-term patterns of climate teleconnections, and reconstructions of the NAO extend back in time only for some centuries (Cook et al. 2002, Timm et al. 2004). More recently, Trouet et al. (2009) accomplished a proxy-based reconstruction of the NAO-index over the last millennium, covering the important late Holocene climate events including the MCA and LIA. Therefore, we focus in our synoptic paleoclimate interpretations on this period with available reference data. We highlight that our record consists of centennial (low frequency) data and indicates only general trends during time periods of the MCA and LIA.

The modern NAO-climate relationships in the study region exhibit highly positive correlations for temperature during each month (Luoto & Helama 2010). Hence, the positive NAO-phase is characterized by milder than average winter weather conditions and the summers tend to be warmer in the study area. However, the NAO-hydroclimate associations are more complex, since during the winter (December to March) the correlations are positive whereas during the spring, summer and autumn (April to November) the correlations appear negative (Luoto & Helama 2010). The chironomid-inferred temperatures from Särkkälampi are based on mean air TJul. Also the chironomid-based water depth reconstruction from Kylmänlampi is based on the taxa–environment association during summer months, which is their primary growing season. However, the transportation of fossil remains of stream chironomids into lake basins may be more complex (Luoto 2010), and it has been suggested that they could be most easily transported during spring floods and hence would indicate the intensity of spring floods, which in turn correlate with winter snow cover (i.e. winter precipitation) (Luoto & Helama 2010). In the present record, the relationship between abundance of stream chironomids in Särkkälampi and NAO patterns appears complicated and it is difficult to pinpoint which season they represent. This relationship seems to be positive during the MCA and the beginning of the LIA (suggesting that the stream taxa indicate winter conditions) but turns negative for the end of the LIA (Fig. 7).

According to our results (Fig. 7), the general conditions during the MCA appeared warm and dry, whereas the prevailing climate during the LIA was cold with fluctuating precipitation. Trouet et al. (2009) reconstructed a persistent phase of positive NAO during the MCA with a subsequent long-term negative phase, and hence weaker NAO conditions, during the LIA (Fig. 7). Analysis of a dataset of global surface temperature changes has also suggested the occurence of this NAO pattern (Mann et al. 2009).

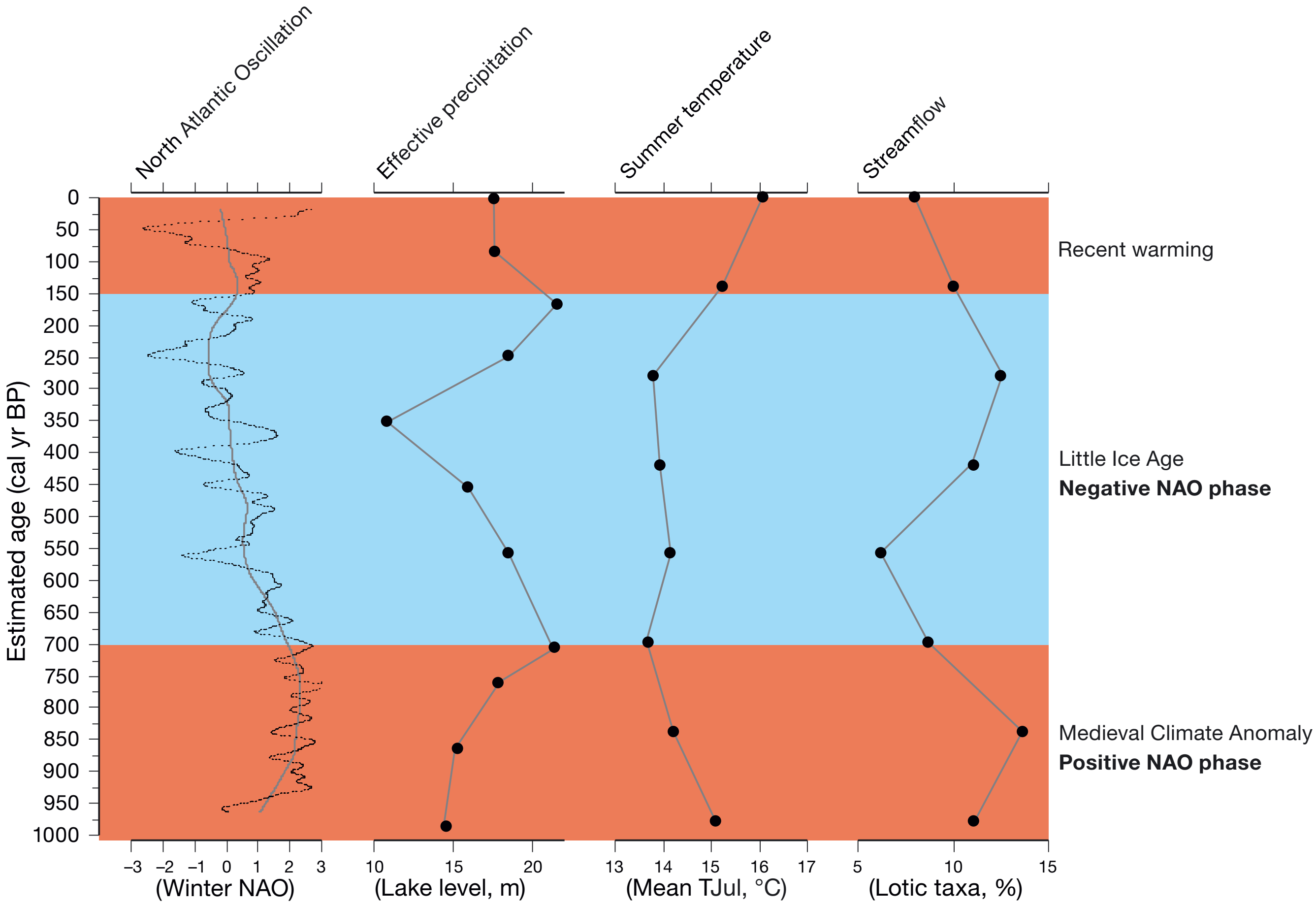

Fig. 7. A ~1000-yr winter North Atlantic Oscillation (NAO) reconstruction based on speleothems and tree-rings (Trouet et al. 2009) compared with lake level (Kylmänlampi), temperature (Särkkälampi) and streamflow (Särkkälampi) reconstructions for eastern Finland. Cool climate phases are marked in blue and warm in red

6. CONCLUSIONS

The results highlight the usability of paleolimnological data to reconstruct past climate changes. More specifically, the versatile species-specific environmental requirements of chironomids make them useful paleoindicators of temperature and effective precipitation. We hypothesized that the enclosed kettle lake Kylmälampi is sensitive to lake level fluctuations, whereas the open-basin Särkkälampi is susceptible to temperature dynamics. Compared to previous paleoclimate evidence showing mostly supporting results, the present reconstructions appear realistic.

The results indicate late Holocene cooling, interrupted by a streamflow event with simultaneously elevated lake levels at ~2500 to 2200 cal yr BP, generally warm and rainless summers during the MCA and cool climate with fluctuating precipitation during the LIA. For the post-LIA period our records indicate increasing air temperatures and average precipitation. The reconstructed summer temperature for the present exceeds any warm event during the past ~3500 years, including the ~4000/3000 cal yr BP event and the MCA, suggesting that the ongoing climate warming is unprecedented in the late Holocene history of eastern Scandinavia.

Despite the relatively coarse resolution of this study, due to low sedimentation rates, reconciliation of the produced paleoclimate data with large-scale atmospheric modes showed that the temperature and precipitation changes are linked to the reconstructed NAO pattern during the last millennium. In agreement with previous indications, our results suggest that a generally positive NAO phase prevailed during the MCA and a negative, though more fluctuating, NAO phase dominated during the LIA. These implications are consistent with the modern regional NAO–climate relationships showing positive correlation with temperature and negative correlation with precipitation during the summer.

This study provides records on temperature and precipitation over the past 3 millennia from eastern Scandinavia that may be useful when assessing the effects and magnitude of the present global change at a regional scale. Our results give support for the dominant role of the NAO pattern on the eastern Scandinavian climate during the past millennium that is important for future spatiotemporal comparisons of NAO–climate interactions. However, the non-analogue rapid warming of the ongoing climate change appears not to be similarly dictated by the NAO as the climate in the past, suggesting that other mechanisms also force the present climate, most evidently the increase in greenhouse gases.

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