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ORIGINAL PAPER

Temperature-precipitation relationship of the Common Era in northern Europe

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Abstract Due to the lack of knowledge on dynamics of the North Atlantic Oscillation (NAO) prior to the last millennium, synchronized records of air temperature and precipitation variability are needed to understand large-scale drivers of the hydroclimate. Here, we use completely synchronized paleolimnological proxy-based records of air temperature and effective precipitation from two Scandinavian lakes with ~2000-year sediment profiles. We show that the relationship between air temperature and precipitation (T/P ratio) is synchronous in both study sites throughout the records suggesting warm and dry conditions at ~300–1100 CE and cold and wet conditions at ~1200–1900 CE. Owing to the significantly increased air temperatures, the most recent T/P ratio has again turned positive. During the first millennium of the Common Era, the T/P mimics patterns in Southern Oscillation index, whereas the second millennium shows response to the NAO index but is also concurrent with solar irradiance shifts. Since our T/P reconstruction is mostly linked with the NAO, we propose the T/P ratio as an indicator of the NAO. Our results from the coherent records provide first-time knowledge on the long-term temperature-precipitation relationship in Northern Europe that increase understanding of the comprehensive hydroclimate system in the region and the NAO dynamics also further back in time.

1 Introduction

It has been previously suggested that the NAO has been dictating the climate of the Northern Hemisphere during the distinct climate episodes of the past 1000 years, including the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) with persistent multi-centennial phases with opposite direction (Bradley et al. 2003; D'Arrigo et al. 2006; Trouet et al. 2009). The cause for the MCA has most likely originated from the North Atlantic, but the causes for the LIA are not well defined owing to its highly variable nature (Wanner et al. 2011; Luoto and Nevalainen 2016; Zawiska et al. 2017). Yet, in addition to a persistent strongly negative NAO index phase during the LIA, it was most likely forced by decreased solar irradiance (including Spörer, Maunder and Dalton solar minima), increased volcanic activity (aerosols), and changes in Atlantic Ocean circulation patterns (Grove 2001; Goosse et al. 2005; Wanner et al. 2011). However, due to the lack of synchronized records of both air temperature and precipitation, there is incomplete knowledge on the temperature-precipitation relationships in northernmost Europe, which is a key climate region responding to the North Atlantic influence (Trigo et al. 2002). It is also one of the major concerns in climate science that reconstructions of the NAO index phases do not extend further back in time than the last 1000 years (Trouet et al. 2009).

Chironomids (Diptera: Chironomidae) are a well-established paleotemperature proxy (Brooks 2006; Walker and Cwynar 2006) with strong correlation in the reconstructed air temperature values with the instrumentally measured meteorological data (Larocque et al. 2009; Luoto and Ojala 2016). Similarly, Cladocera (Crustacea) have been shown to be sensitive paleoindicators of lake water depth (Korhola et al. 2005; Amsinck et al. 2006), reflecting changes in effective precipitation (precipitation-evaporation) in hydrologically

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responsive basins. Although it has not been possible to validate changes in water depth against instrumental data, the Cladocera-based reconstructions have been shown to provide the same signal as treering-based precipitation reconstructions (Nevalainen et al. 2013). In this study, we use downcore records where fossil chironomid assemblages are used to quantitatively reconstruct past changes in mean July air temperature (TJul) and fossil Cladocera assemblages to reconstruct lake depth (i.e., effective precipitation) applying the transfer function (calibration-in-space) approach. The previously available reconstructions from southern and eastern Finland have been validated against independent proxy records. Here, we use these records in conjunction in order to produce a ratio between air temperature and precipitation (T/P) that can be used to indicate hydroclimate and as a potential extension to the pre-existing records of North Atlantic forcing. Since we use independent proxy records from the same sediment subsamples from two different study sites, the air temperature and precipitation records are entirely synchronized and comparable.

2 Methods

2.1 Study sites

Proxy-based records from two hydroclimatically sensitive boreal lakes were selected to this study (Fig. 1). Iso Lehmälampi (60°20′N, 24°36′E, 92 m a.s.l.) is a naturally acidic undisturbed ultraoligotrophic lake in an upland area in southern
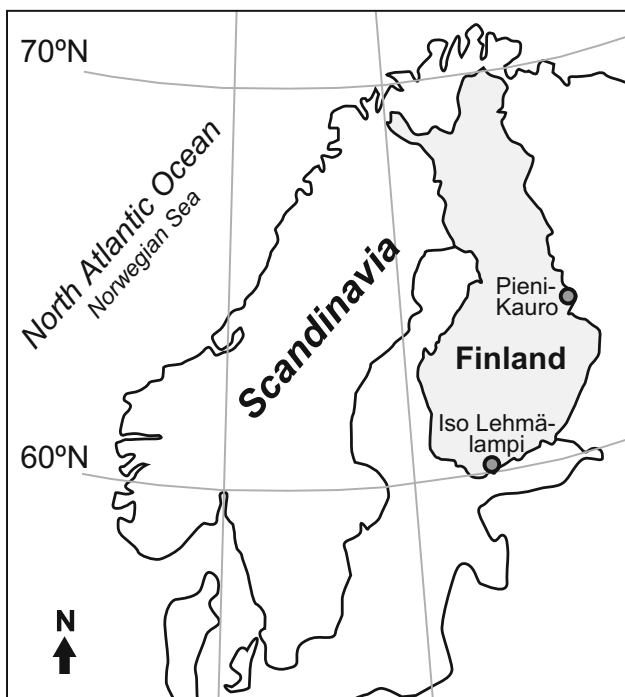

Fig. 1 Location of the study sites Iso Lehmälampi (southern Finland) and Pieni-Kauro (eastern Finland) in Northern Europe

Finland, whereas Pieni-Kauro (64°17′N, 30°07′E, 188 m a.s.l.), located close to the Russian border in eastern Finland, is a remote dystrophic lake. Iso Lehmälampi is a closed basin with a small drainage area but Pieni-Kauro is an open basin (paternoster lake) with larger drainage. More information about the sites can be found from previous publications (Nevalainen et al. 2008; Luoto 2010).

The modern and past air temperature and precipitation relationship in Finland have been shown to be related to the NAO (Korhonen 2007; Helama and Holopainen 2012). There exists a positive correlation between both summer and winter air temperature and the NAO index phase, whereas in case of precipitation, the correlation is positive during summer and negative during winter (data derived from Kalnay et al. 1986). These settings provide basis for tracking the long-term temperature-precipitation relationship at our study site.

2.2 Quantitative reconstructions

The chironomid-based reconstructions of mean July air temperature (TJul) and Cladocera-based reconstructions of water depth for Iso Lehmälampi and Pieni-Kauro have been previously published (Luoto 2009a; Luoto and Helama 2010; Nevalainen and Luoto 2012; Nevalainen et al. 2013). In both of the radiocarbon-dated sediment cores, chironomid and Cladocera analyses have been performed from the same sediment subsamples enabling the direct comparison between the results without any potential bias in chronological control. The chironomid-based temperature reconstructions used the Finnish multilake calibration model (78 sites) applying weighted averaging-partial least squares (WA-PLS) technique (Luoto 2009b). The model has a cross-validated coefficient of determination of 0.78, a root mean squared error of prediction of 0.72 °C, and a maximum bias of 0.79 °C. The Cladocera-based water depth reconstructions were run with an intra-lake model constructed using weighted averaging and classical deshrinking regression (Nevalainen and Luoto 2012). This model has a cross-validated coefficient of determination of 0.79, a root mean squared error of prediction of 0.79 m, and a maximum bias of 1.74 m.

2.3 Temperature-precipitation relationship and data on external forcing

In this study, to equalize the control of the air temperature and lake level reconstructions and to prevent the overruling contribution of one variable over the other due to differences in units (°C versus m), they were standardized to represent relative variability in each of the reconstructions (i.e., the lowest reconstructed value = 0 and the maximum value = 1). In so doing, temperature and lake level (indicating effective precipitation) have equal effect in the air temperature/precipitation (T/P) ratio (mean air TJul/water depth). This ratio is deduced

to reflect the air temperature to precipitation relationship in a way that low values reflect conditions of decreased air temperature and elevated precipitation, whereas high values reflect elevated air temperature and decreased precipitation. LOESS smooth (span 0.3) was applied to avoid any potential bias resulting from chronological uncertainties. LOESS was also used to create a consensus curve combining both time series to provide a consistent T/P reconstruction that can be further linked with the positive and negative NAO index phases.

A ~1000-year 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 air temperature changes in Northern Europe. In addition, reconstruction of a precipitation-based Southern Oscillation Index (SOIpr) based on proxy precipitation records from Indonesia (salinity reconstruction based on planktonic-foraminifera $\delta^{18}O$ and Mg/Ca ratio) and Galapagos (grain size-based lake level reconstruction) for the past 2000 years (Yan et al. 2011) and an average total solar irradiance (TSI) relative to the solar cycle minimum of the year AD 1986 based on relationship between total solar irradiance and the open solar magnetic field (cosmogenic radionuclide ^{10}Be measured in ice cores) (Steinhilber et al. 2009) were used for comparison. The data on atmospheric and solar forcing were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (www.ncdc.noaa.gov). Linear dependence between the LOESS-adjusted trends in the consensus T/P ratio, and the NAO was measured using the Pearson product-moment correlation coefficient (r) and the associated level of statistical significance (p).

Fig. 2 Chironomid-inferred mean July air temperature (TJul) and Cladocera-inferred water depth from lakes Iso Lehmälampi (southern Finland) and Pieni-Kauro (eastern Finland). The reconstructions are standardized according to their relative variation (minimum value = 0, maximum value = 1)

3 Results and discussion

Our records of summer air temperature and effective precipitation show similar trends, yet having clear regional differences in the high-frequency variability between the study sites in eastern and southern Finland (Fig. 2). When the air temperature and precipitation records are combined to form regional curves of the T/P ratio (Fig. 3), the trends between different localities are distinctly similar. This suggests that despite local differences in variability, the general large-scale climate development has clear imprint in both sediment archives. The longer record from southern Finland shows low T/P values between 0 and 300 CE (Fig. 3) suggesting cold and wet climate conditions at the time reflecting the individual reconstructions of air temperature and water level variation (Fig. 2). Following this, both records show high T/P values until ~1200 CE indicating that the climate was warmer and drier. This period includes the MCA, which has been
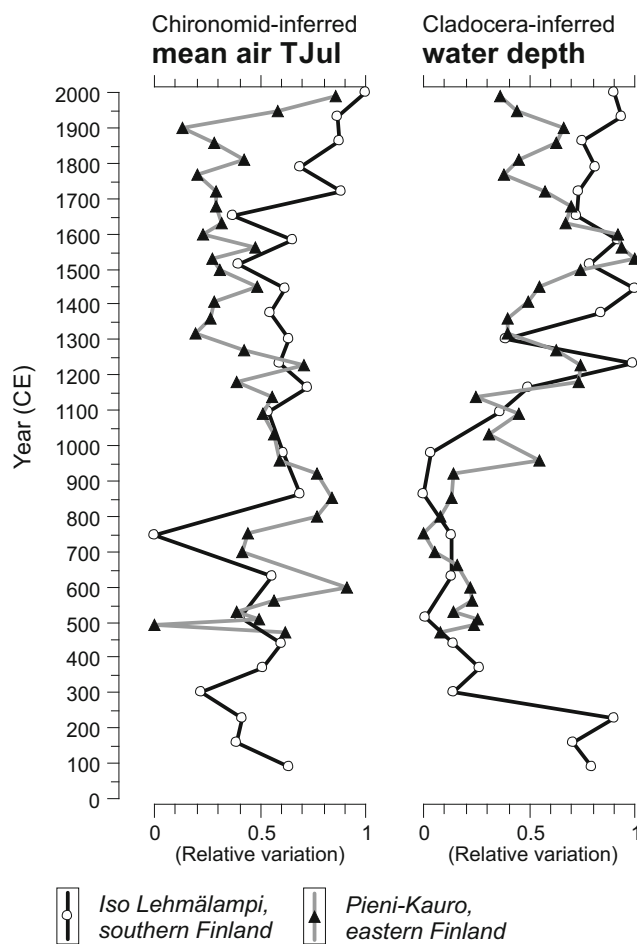
described to have increased air temperatures and decreased precipitation encompassing a multicentennial megadrought (Helama et al. 2009; Cook et al. 2015). However, in our records, the peak T/P ratio occurs before this and the signal during the MCA is rather muted, especially in the site from eastern Finland (Fig. 3). In agreement with previous findings (Wanner et al. 2011), during the LIA, the low T/P ratio suggest cold and moist conditions in both records. The cold period associated with the LIA initiated following the MCA at ~1200–1300 CE but lasted longer in eastern Finland until ~1900 CE that is also evident from previous paleoclimatological studies (Luoto and Nevalainen 2015). In both records, the coldest and wettest conditions prevailed between 1500 and 1650 CE (Fig. 3), close to the culmination of the LIA (Grove 2001). Again in agreement, both our records show development in the recent times towards higher T/P values (Fig. 3) resulting from the increased air temperatures rather than any distinct change in precipitation (Fig. 2).
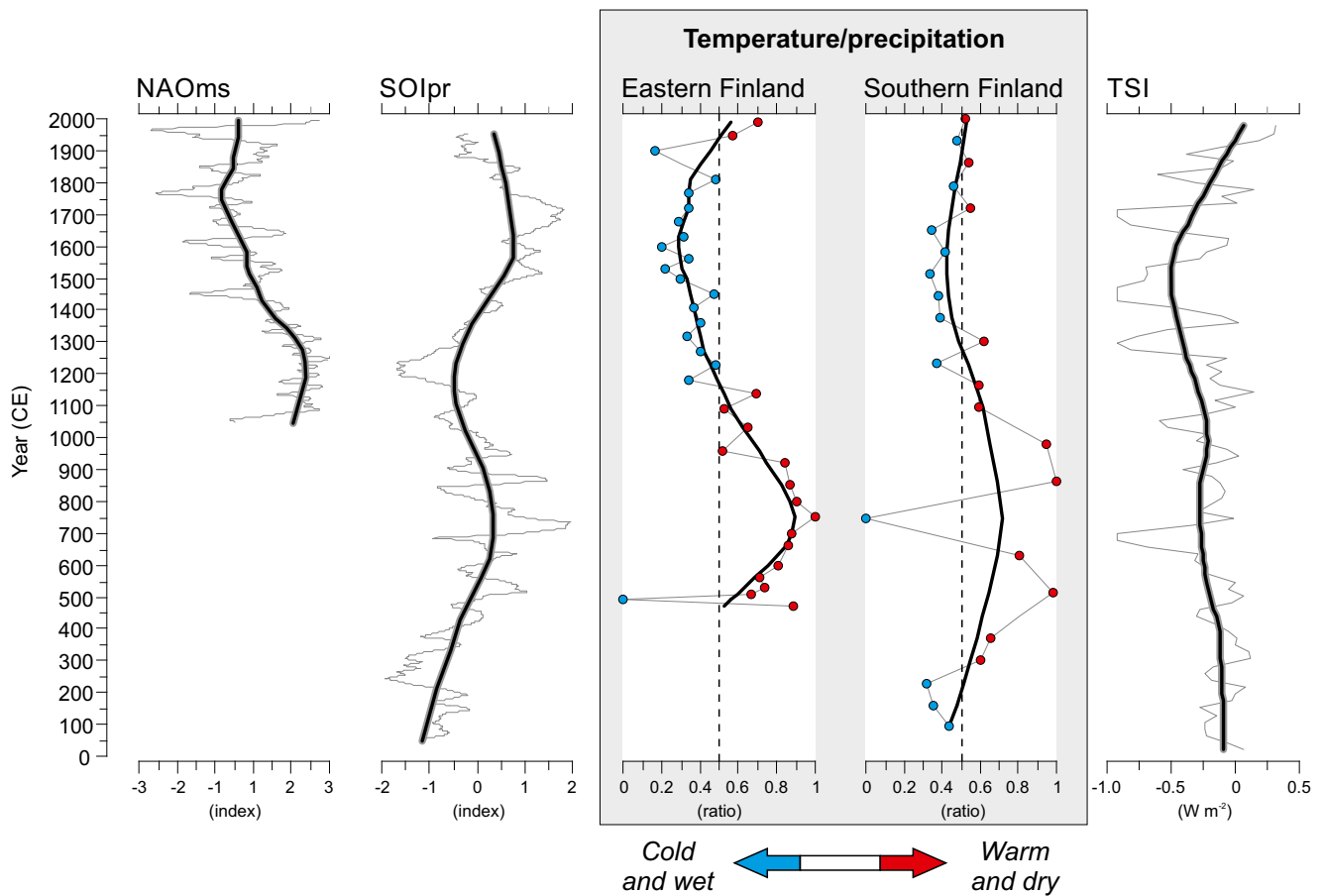
Fig. 3 The temperature-precipitation relationship represented as the ratio between standardized (relative variation) chironomid-inferred mean July air temperature (TJul) and Cladocera-inferred water depth (i.e., effective precipitation) from southern (Iso Lehmälampi) and eastern (Pieni-Kauro) Finland. The results are compared with reconstructions of a winter North Atlantic Oscillation index (Morocco-Scotland difference: NAOms) (Trouet et al. 2009), precipitation-based Southern Oscillation Index (SOIpr) (Yan et al. 2011), and total solar irradiance (TSI) (Steinhilber et al. 2009). The trend lines use LOESS smoothing (span 0.3)

The first ~1300 years in our T/P records show connection with the precipitation-based Southern Oscillation Index (SOIpr) reconstruction (Yan et al. 2011) with negative SOIpr values concurrent with cold and wet conditions and positive SOIpr values with warm and dry conditions in Scandinavia (Fig. 3). At ~700 CE, there is a decrease in the T/P ratio in the record from southern Finland, which is not evident in the SOIpr. Instead, this period with the minimum temperatures of the Common Era (Fig. 2) corresponds with a grand minimum in solar activity (Steinhilber et al. 2009) indicated by the TSI reconstruction (Fig. 3). Although solar forcing is one of the main drivers of the El Niño/Southern Oscillation (ENSO) pattern over interglacial-glacial timescales (Tudhope et al. 2001), the direct influence of reduced sun activity appears to have overruled the influence of the ENSO pattern over a shorter timescale at the study site. Since there are no valid reconstructions of the NAO available that extend prior to 1000 CE, it is not possible to compare our results with the North Atlantic forcing during the first millennium. However, during the last 1000 years, when a NAO-index reconstruction

is available (Trouet et al. 2009), both our records show similar trends with NAO variability having negative NAO-index phases simultaneous with low T/P and positive phases with high T/P (Fig. 3). This is confirmed by the Pearson's r showing a statistically significant correlation between the LOESS trends in the consensus T/P ratio and the NAO index ($r = 0.44$, $p = 0.007$). These results are in direct agreement with previous studies that have suggested that the MCA and LIA were driven by changes in the North Atlantic (Wanner et al. 2011). It has also been speculated that the dry conditions in Scandinavia during the MCA were linked with the ENSO pattern (Helama et al. 2009) that agrees with our results, which show similarly increased T/P values indicating warm and dry climate at the time (Fig. 3). Despite that both teleconnections may be driving the climate of Northern Europe, the results clearly demonstrate that the NAO pattern is the more consistent forcing in the T/P records. It is also noteworthy that during the past 1000 years, the TSI reconstruction is synchronous with the T/P variability suggesting that also solar activity has a role in the general hydroclimate of Northern Europe, in a similar
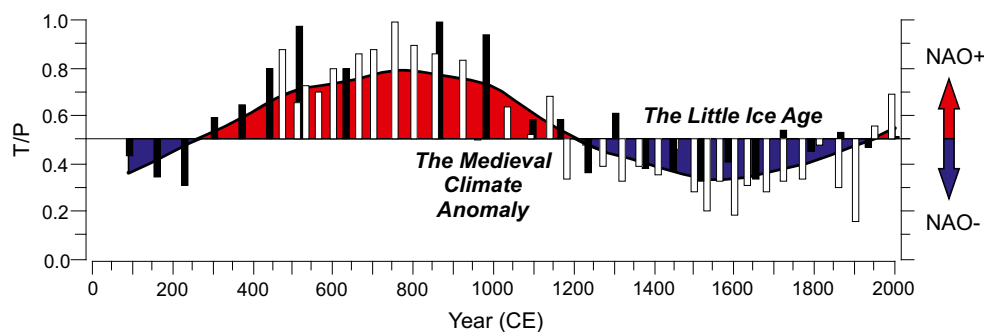
Fig. 4 Combined temperature-precipitation relationship (T/P) derived from proxy records from southern (*black bars*) and eastern (*white bars*) Finland applying LOESS smoothing (span 0.3). The *blue shade* indicating T/P values <0.5 (cold and wet) and the *red shade* indicating T/P values >0.5 (warm and dry) are deduced to reflect negative and positive North Atlantic Oscillation (NAO) index phases, respectively. Samples with zero values have been removed

way as it also drives the NAO phases (Thiéblemont et al. 2015). Recently, the increase in atmospheric greenhouse gases has raised air temperatures (Karl and Trenberth 2003), but at the same time, there appears to be divergent trends in the precipitation dynamics between southern and eastern Finland (Fig. 2). Therefore, it is likely that the forcing factors that have dictated the T/P ratio in the past do not operate in a similar way today, or in the future, due to the persistent anthropogenic influence of increased greenhouse gases on surface air temperatures (Alley et al. 2003). In fact, using climate model simulations, it has been demonstrated that the recent shift of the NAO over Europe is a result of anthropogenic greenhouse forcing (Ulbrich and Christoph 1999).

Since the previous studies and the present results suggest that the NAO has been the most important driver of the air temperature-precipitation relationship in the eastern parts of Northern Europe, we here propose the T/P ratio as an indicator of the NAO phases. When combining the T/P reconstructions from our study sites to form a smoothened consensus curve, the results provide a rather consistent picture of the air temperature-precipitation relationship originating from the North Atlantic (Fig. 4). In the future, using similar approaches and synchronized records of air temperature and precipitation, it may be possible to extend the NAO reconstructions to cover the entire Holocene Epoch.

4 Conclusions

Although similar in trends, the air temperature and precipitation dynamics in our records showed differences in their high-frequency variability between the two study sites in southern and eastern Finland. Regardless of this variability in particular climate variables, the T/P ratios were very similar indicating consistent regional hydroclimatic imprint. We were able to link the first millennium of the Common Era with changes in the SOI and second millennia with the NAO index. Clear connections were also found between the T/P ratio and solar

activity, which explains a major part of the teleconnection patterns. Owing to the absence of NAO reconstructions longer than 1000 years, the present results can provide important implications not only on the past regional air temperature and precipitation relationships but also on the changes that have occurred in the North Atlantic sector further back in time.

References

Alley RB, Marotzke J, Nordhaus WD et al (2003) Abrupt climate change. Science 299:2005–2010

Amsinck SL, Strzelczak A, Bjerring R, Landkildehus F, Lauridsen TL, Christoffersen K, Jeppesen E (2006) Lake depth rather than fish planktivory determines cladoceran community structure in Faroese lakes–evidence from contemporary data and sediments. Freshw Biol 51:2124–2142

Bradley RS, Hughes MK, Diaz HF (2003) Climate in Medieval time. Science 302:404–405

Brooks SJ (2006) Fossil midges (Diptera: Chironomidae) as palaeoclimatic indicators for the Eurasian region. Quat Sci Rev 25:1894–1910

Cook ER, Seager R, Kushnir Y et al (2015) Old world megadroughts and pluvials during the Common Era. Sci Adv 1:e1500561

D'Arrigo R, Wilson R, Jacoby G (2006) On the long-term context for late twentieth century warming. J Geophys Res 111:D03103

Goosse H, Renssen H, Timmermann A, Bradley RS (2005) Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. Quat Sci Rev 24:1345–1360

Grove JM (2001) The initiation of the "Little Ice Age" in regions around the North Atlantic. Clim Chang 48:53–82

Helama S, Holopainen J (2012) Spring temperature variability relative to the North Atlantic Oscillation and sunspots—a correlation analysis with a Monte Carlo implementation. Palaeogeogr Palaeoclimatol Palaeoecol 326:128–134

Helama S, Meriläinen J, Tuomenvirta H (2009) Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval climate anomaly. Geology 37:175–178

Kalnay E, Kanamitsu M, Kistler R et al (1986) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–472

Karl TR, Trenberth KE (2003) Modern global climate change. Science 302:1719–1723

Korhola A, Tikkanen M, Weckström J (2005) Quantification of Holocene lake-level changes in Finnish Lapland using a cladocera–lake depth transfer model. J Paleolimnol 34:175–190

Korhonen J (2007) Discharge and water level variations in lakes and rivers in Finland. Finnish Environ 45:1–120

Larocque I, Grosjean M, Heiri O, Bigler C, Blass A (2009) Comparison between chironomid-inferred July temperatures and meteorological data AD 1850–2001 from varved Lake Silvaplana, Switzerland. J Paleolimnol 41:329–342

Luoto TP (2009a) A Finnish chironomid- and chaoborid-based inference model for reconstructing past lake levels. Quat Sci Rev 28:1481–1489

Luoto TP (2009b) Subfossil Chironomidae (Insecta: Diptera) along a latitudinal gradient in Finland: development of a new temperature inference model. J Quat Sci 24:150–158

Luoto TP (2010) Hydrological change in lakes inferred from midge assemblages through use of an intralake calibration set. Ecol Monogr 80:303–329

Luoto TP, Helama S (2010) Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval climate anomaly and Little Ice Age. Quat Sci Rev 29:2411–2423

Luoto TP, Nevalainen L (2015) Late Holocene precipitation and temperature changes in northern Europe linked with North Atlantic forcing. Clim Res 66:37–48

Luoto TP, Nevalainen L (2016) Quantifying climate changes of the Common Era for Finland. Clim Dyn. doi:10.1007/s00382-016-3468-x

Luoto TP, Ojala AEK (2016) Meteorological validation of chironomids as a paleotemperature proxy using varved lake sediments. The Holocene. doi:10.1177/0959683616675940

Nevalainen L, Luoto TP (2012) Intralake training set of fossil Cladocera for paleohydrological inferences: evidence for multicentennial drought during the Medieval climate anomaly. Ecohydrology 5:834–840

Nevalainen L, Luoto TP, Sarmaja-Korjonen K (2008) Late Holocene water-level changes in Lake Iso Lehmälampi, southern Finland, reflected in subfossil cladocerans and chironomids. Studia Quaternaria 25:33–42

Nevalainen L, Helama S, Luoto TP (2013) Hydroclimatic variations over the last millennium in eastern Finland disentangled by fossil Cladocera. Palaeogeogr Palaeoclimatol Palaeoecol 378:13–21

Steinhilber F, Beer J, Fröhlich C (2009) Total solar irradiance during the Holocene. Geophys Res Lett 36:L19704

Thiéblemont R, Matthes K, Omrani NE, Kodera K, Hansen F (2015) Solar forcing synchronizes decadal North Atlantic climate variability. Nat Commun 6:8268

Trigo RM, Osborn TJ, Corte-Real JM (2002) The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. Clim Res 20:9–17

Trouet V, Esper J, Graham NE, Baker A, Scourse JD, Frank DC (2009) Persistent positive North Atlantic Oscillation mode dominated the Medieval climate anomaly. Science 324:78–80

Tudhope AW, Chilcott CP, McCulloch MT, Cook ER, Chappell J, Ellam RM, Lea DW, Lough JM, Shimmield GB (2001) Variability in the El Niño-southern Oscillation through a glacial-interglacial cycle. Science 291:1511–1517

Ulbrich U, Christoph M (1999) A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. Clim Dyn 15:551–559

Walker IR, Cwynar LC (2006) Midges and palaeotemperature reconstruction—the North American experience. Quat Sci Rev 25:1911–1925

Wanner H, Solomina O, Grosjean M, Ritz SP, Jetel M (2011) Structure and origin of Holocene cold events. Quat Sci Rev 30:3109–3123

Yan H, Sun L, Wang Y, Huang W, Qium S, Yang C (2011) A record of the Southern Oscillation index for the past 2,000 years from precipitation proxies. Nat Geosci 4:611–614

Zawiska I, Luoto TP, Nevalainen L, Tylmann W, Jensen TC, Obremska M, Słowiński M, Woszczyk M, Schartau AK, Walseng B (2017) Climate variability and lake ecosystem responses in western Scandinavia (Norway) during the last millennium. Palaeogeogr Palaeoclimatol Palaeoecol 466:231–239