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New evidence of warm early-Holocene summers in subarctic Finland based on an enhanced regional chironomid-based temperature calibration model

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ABSTRACT

Paleoclimate reconstructions based on biological proxies present methodological challenges, especially during non-analog conditions, such as the early Holocene. Here, two chironomid-based training sets from Finland were amalgamated to create a more accurate transfer function of summer air temperature. The aim was to reconstruct Holocene paleoclimate in northernmost Lapland, in an area that has been either too warm or too cold for reliable reconstructions using the original calibration models. The results showed that the combined calibration model had improved performance statistics. The temperature trends inferred from the downcore chironomid record using the original and combined models were very similar. However, there were major changes in their absolute values with the combined model showing greatly improved accuracy. The chironomid-based temperature reconstruction showed significant correlation with the previous pollen-based reconstructions from northwestern Finnish Lapland. However, differences were observed in the temperature trends of the early Holocene, when the chironomid-inferred temperatures rapidly increased, but the pollen-based reconstructions lagged behind suggesting that a cool climate continued for much longer. However, similar to the chironomid record, new plant macrofossil evidence from northwestern Finland also showed warmer-than-present early Holocene temperatures. Therefore, we conclude that the early Holocene was probably warm in northern Lapland.

Introduction

Climate change projections for the future suggest increased temperatures outside the magnitude of observational records (Carter et al., 2004). Therefore, knowledge of past climates is needed to increase our understanding of climate variability and its influences on the natural environment. Due to the short time span of observational records (Vesajoki and Holopainen, 1998), paleoclimatological proxies from geological and related archives are invaluable. Paleolimnological data from lake sediments provide a major data source for understanding causes and dynamics of climate changes (Smol, 2008) and one of the major proxies used for paleoclimatic inferences are (sub)fossil remains of chironomids (Insecta: Diptera: Chironomidae) (Brooks, 2006; Walker and Cwynar, 2006; Eggermont and Heiri, 2012). Typical species composition can be assigned for different climate conditions using training sets collected from multiple lakes along a temperature gradient. These training sets of modern species–environment relations can be used to construct calibration models (calibration-in-space) to quantitatively reconstruct past climate dynamics from downcore sediment profiles (Brooks and Birks, 2001). In general, regional calibration models perform most reliably on downcore sediment records, except for late glacial chironomid records which often contain taxa that are no longer regionally abundant (Larocque-Tobler, 2010), whereas application of chironomid-based inference models based on taxon optima from different biogeographical or climatic regions has a larger potential for error (Heiri et al., 2011).

The rapid response of insect communities to climate change (Elias, 1991) and the sensitivity of chironomids, in particular, to prevailing temperature conditions have made fossil chironomids one of the most utilized biological proxies in paleoclimatology. Recent methodological advancement, including improvements in fossil taxonomy (Brooks et al., 2007), has increased the reliability of chironomid-based temperature reconstructions (Heiri and Lotter, 2010), while in the meantime, more accurate paleoclimate reconstructions are required for putting the present climate change into a long-term perspective (Wanner et al., 2008). Although there is some debate on the relative roles of direct versus indirect effects of temperature in shaping the chironomid–climate correlation and apparent inconsistencies in chironomid-inferred temperatures (Brodersen et al., 2004, 2008; Velle et al., 2010, 2012), chironomids are accepted as one of the most useful paleoindicators of temperature (Brooks, 2006; Walker and Cwynar, 2006; Brooks et al., 2012; Eggermont and Heiri, 2012). To establish reliable chironomid-based temperature reconstructions, calibration data sets and downcore sites must be carefully selected, ecological characteristics comprehensively

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considered, fossil assemblages evaluated for modern analogs, and reconstructions tested for their significance and validated against other proxy records (Velle et al., 2010; Brooks et al., 2012).

In this study, through taxonomic harmonization, two existing chironomid-based training sets from Finland (Nyman et al., 2005; Luoto, 2009a) are amalgamated to provide more reliable and accurate regional paleoclimate reconstructions. The longer temperature gradient of the combined training set is hypothesized to strengthen the relationship between chironomid species assemblages and temperature, and the increased number of sites and taxa is expected to enhance the precision of estimated taxon optima that would lead to more accurate paleoclimate reconstructions. The developed model is applied to an AMS ^{14}C dated Holocene sediment profile from Lake Várddoaijávri, located in northernmost Finnish Lapland, in an area where the modern summer temperatures are either in the upper or lower end of the temperature gradients covered by the existing regional chironomid-based inference models, which potentially makes the original models unreliable for this site. A special focus of this paper is on the regional temperature development during the early Holocene, when pollen-based reconstructions have indicated low temperatures until ~8000–7000 cal yr BP (Seppä and Birks, 2001, 2002), but contradictory evidence exists from the area that the climate was warm already during the early Holocene (Korhola et al., 2002a; Väliranta et al., 2005; Sarmaja-Korjonen et al., 2006; Szeroczyńska et al., 2007). For comparison with the chironomid-based reconstruction, we also use plant macrofossil records from three sites to reconstruct the early Holocene temperature development in northern Lapland.

Regional setting

The original chironomid-based training set from northwestern Finnish Lapland (67°82′–69°27′N, 20°67′–24°87′E) consists of 62 lakes of which 17 are located in barren tundra, 26 in mountain birch woodland and 19 in pine and birch forest zone (Table 1; Fig. 1). The bedrock consists of acidic Precambrian plutonic and metamorphic rocks and in the northernmost study area of Palaeozoic schists and gneisses. The mean July air temperature (T_{Jul}) varies from 7.9 to 13.8°C along an altitudinal gradient from 197.5 to 1024.4 m asl. The sampling depth of the lakes varies from 0.9 to 25 m. The chironomid-based training set from northwestern Lapland was originally collected by Olander et al. (1999) and Korhola et al. (2002a), and the chironomid identifications were updated by Nyman et al. (2005). The chironomid-based temperature calibration model used as a part of the new combined dataset in this study was first introduced and used by Seppä et al. (2002). More details about the study area and sites are given in Weckström and Korhola (2001) and Korhola et al. (2002b).

Table 1
Comparison of the chironomid-based temperature calibration sets from Finland.

	Nyman et al. (2005)	Luoto (2009a)	New combined
Number of sites	62	77	139
Barren tundra sites	17	1	18
Mountain birch woodland sites	26	11	37
Pine and birch forest sites	19	11	30
Spruce, pine, and birch forest sites	0	54	54
Mean air T_{Jul} gradient (°C)	5.9 (7.9–13.8)	5.8 (11.3–17.1)	9.2 (7.9–17.1)
Best model type	WA-PLS, comp. 2	WA-PLS, comp. 1	WA-PLS, comp. 2
Number of taxa in model	71	84	117
R^2_{jack}	0.75	0.78	0.88
RMSEP (°C)	0.754	0.721	0.839
Mean bias (°C)	0.009	0.018	0.005
Maximum bias (°C)	1.095	0.794	1.088

The original training set along the latitudinal gradient in Finland (60°13′–69°53′N, 22°00′–30°13′E) by Luoto (2009a) consists of 77 lakes (with 5 outliers removed). One of the lakes is located in barren tundra, 11 in mountain birch woodland, 11 in pine and birch forest zone and 54 in mixed boreal forests with spruce, pine, and birch (Fig. 1; Table 1). The training set is situated in the central part of the Precambrian Fennoscandian Shield. In general, rocks of the shield are younger towards southwest Finland occupying the main part of the transitional zone between dominantly Archaean and Palaeoproterozoic rocks, mostly granites. The mean air T_{Jul} varies within the training set between 11.3 and 17.1°C and elevation between 11.6 and 404.0 m asl. The gradient in sampling depth is from 0.5 to 9.0 m. The study area and sites are described in more detail by Luoto (2009a) and Kultti et al. (2011).

The downcore study site, Lake Várddoaijávri (69°53′N, 26°31′E), is situated in northeastern Finnish Lapland, close to the Norwegian border and outside the region of the training set from northwestern Finnish Lapland and at the northern part of the latitudinal training set (Fig. 1). The ~26 ha lake with maximum depth of ~5 m lies at 409.4 m asl. The lake is located in barren tundra with a rocky surface with patchy thin soil cover. The catchment area is ~150 ha with two small seasonal streams flowing into the lake from the south and southeast. The area belongs to a granulite belt. The vegetation in the catchment of Lake Várddoaijávri consists of low shrubs, lichen and mosses. The climate in the area of the lake is subarctic with an air temperature of −2.6°C and mean air T_{Jul} of 11.3°C. The pH of the lake was 6.3 on April 2005. The ultraoligotrophic lake is currently occupied by a small-bodied Arctic char (*Salvelinus alpinus* L.) population, while other fish species are absent (Lehtonen, 1998). For more details on the site, see Luoto and Sarmaja-Korjonen (2011).

Material and methods

Sampling and sediments

The chironomid-based training sets from northwestern Finnish Lapland (Nyman et al., 2005) and from the latitudinal gradient in Finland (Luoto, 2009a) are based on fossil assemblages in the uppermost 0–1 cm of lake sediments. The sampling depths vary in both of the training sets (from sublittoral to profundal samples) and it should be noted that they do not necessarily equate to the maximum lake depths. A 296-cm downcore sediment sequence from Lake Várddoaijávri was cored from ice cover at a water depth of 393 cm in April 2005 using a Russian peat corer. The whole sediment profile consisted of gyttja. The age–depth model is based on eight AMS radiocarbon dates (with two outliers excluded) and on retreat of the Weichselian ice sheet from the area between ~11,500 and 11,000 cal yr BP (Johansson and Kujansuu, 2005). Details on the training sets (Olander et al., 1999; Korhola et al., 2002a; Nyman et al., 2005; Luoto, 2009a; Kultti et al., 2011) and the core (Luoto and Sarmaja-Korjonen, 2011) can be found in the previous publications.

Fossil analyses and numerical methods

Fossil chironomid analyses were performed applying standard methods (see Olander et al., 1999; Nyman et al., 2005; Luoto, 2009a; Luoto and Sarmaja-Korjonen, 2011) at 1-cm slices in the training sets and at 3–5 cm intervals from 1-cm slices in the downcore sequence. The identification was mainly based on the identification guides by Wiederholm (1983) and Brooks et al. (2007). Descriptions by Heiri et al. (2004) and Rieradevall and Brooks (2001) were used to identify the Tanytarsini and Tanypodinae, respectively. The nomenclature for the chironomid morphotypes in the new combined training set follows that of Brooks et al. (2007). Taxonomic harmonization of the two training sets was achieved through close collaboration between the chironomid analysts.