Climatic change at lake Hämelsee

a chironomid-based reconstruction of temperatures during the Younger Dryas – Preboreal transition

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Abstract

Despite the fact that the transition from the last ice age into the Holocene has been studied widely across Europe, there is still a strong need for additional accurate quantitative reconstructions of climate in order to better understand the machanisms that caused this shift in climate. In this study I reconstruct Late-Glacial and Holocene conditions at lake Hämelsee (Lower Saxony, Germany) using subfossil chironomid head capsules. The chironomid assemblages in lake Hämelsee indicate one large climatic event at ~12,000 BP, followed by two minor events ~12,000 and 11,260 BP. Decreases in cold-indicating taxa (e.g. *Tanytarsus lugens*-type) in favor of warm-indicating taxa (e.g. *Lauterborniella*) indicate changing air temperatures at the lake. I applied a chironomid-temperature transfer-function to the fossil data to quantify these changes. The chironomid-inferred temperatures are characterized by a rapid 4.2 °C increase in temperatures at the onset of the Holocene, followed by a more gradual warming and cooling event of roughly 1 and 1.5 °C, respectively. These minor events may correspond to the Friesland and Rammelbeek phases of the Preboreal oscillation. Non-chironomid taxa, including *Chaoborus flavicans* and *Plumatella*, suggest increased stratification and eutrophication of the lake simultaneous with the strong temperature increase at the onset of the Holocene. The amplitude of the temperature increase corresponds well to those observed in neighbouring sites, especially to Friedlander Groβe Wiese (Germany). This study shows the suitability of chironomids as a palaeoecological proxy, and fills a gap in the network of studied lakes in northwest Europe.

1. Introduction

Contemporary climate change, and the anthropogenic forces acting upon it, is a subject of much debate. Mean global temperatures have increased over the last century, and much of this has been attributed to human activity, e.g. via the release of greenhouse gases by industries (IPCC, 2013). It is likely that such activities have influenced climate change, but natural changes have been occurring for much longer and reconstructions of past climate change may help us to better anticipate future change.

Palaeoclimatological research has shown that climate change has occurred naturally over the course of the last several million years. The Quaternary (2.5 Ma – present) is characterized by many fluctuations in climate, with cold glacial time periods being interspersed by warmer interglacials. The most recent of these glacial periods lasted until ca. 11.7 ka BP, culminating in a series of short alternating stadials and interstadials. The last of the stadials is known as the Younger Dryas (12.8 – 11.7 ka BP; Rasmussen *et al.*, 2006), which at its end transitioned into the current interglacial,

the Holocene. This transition from the Late-Glacial into the Holocene consisted of a sudden shift in climate, especially in areas within the Atlantic region. The cold conditions prevalent during the Younger Dryas rapidly shifted towards the warmer conditions of the Preboreal, the start of the Holocene (Brooks & Birks, 2001; Heiri *et al.*, 2007; Van Asch *et al.*, 2012). The temperature changes during the Younger Dryas–Preboreal transition occurred within the span of less than a century (Rasmussen *et al.,* 2006). This allowed for the development of new vegetation types (Hoek, 1997), as well as dramatically changing the landscape as the glaciers retreated. The exact conditions under which global temperatures rose by several degrees centigrade in less than a century during this period remain unclear. It is important to better understand the circumstances surrounding such extreme climatic change, as such knowledge may assist in predicting the course of future climatic changes. Information on the (a)biotic circumstances during this period of time cannot be acquired directly, and it is for this reason that palaeoecological research focuses on proxies found within a spectrum of different sources,

such as lake sediments. Many lakes and other such sites (e.g. bogs) have already been studied within northwest Europe, but knowledge gaps remain in several regions. In Lower Saxony, Germany, lies the northernmost site containing varved sediment layers throughout large parts of its sediment record. This site, lake Hämelsee, contains a full record of the Late-Glacial and Holocene (Merkt & Müller, 1999).

The European INTIMATE initiative ("*Int*egrating *I*ce core, *Ma*rine, and *Te*rrestrial records"; COST Action ES0907) selected the Hämelsee site to perform a detailed analysis of the Late-Glacial time period. Two sediment cores, *HAEM13-1* and *HAEM13-2*, were recovered from the lake during fieldwork in July 2013. These two cores, when combined, form a sediment record that spans the entire interval from the Late-Glacial to the present. As part of the overarching INTIMATE Example project, the sediment will be analysed using a wide range of methods to further study Late-Glacial lake and climate conditions at this site. The selected proxies include geochemical (e.g. biomarkers), sedimentological (e.g. Loss-On-Ignition), and microfossil analytic techniques (e.g. pollen). This study aims to add a new source of information to the overarching research project by studying sub-fossil chironomids found within the sediments of lake Hämelsee.

The analysis of sub-fossil head capsules of chironomid larvae (Family: Chironomidae; Order: Diptera) can be used to accurately infer past summer water and air temperatures, especially those of the Late-Glacial period (Brooks, 2006). Chironomids, or non-biting midges, are well-suited for such reconstructions for several reasons (Brooks *et al.*, 2007). They have short generation times, and the adults are highly mobile, allowing them to rapidly seek out new habitats. Additionally, the Chironomidae are ubiquitous and consist of many stenotopic species. It is therefore possible to find chironomids in nearly every freshwater system, with different ecological circumstances being reflected by different assemblages. Their characteristics allow them to rapidly adapt to changing ecological conditions, both local and

regional. The relative ease with which the different taxa can be distinguished from each other allows for the accurate reconstruction of the past chironomid fauna of a lake, and subsequently deduce the corresponding ecological conditions. Furthermore, the head capsules are very abundant in lake sediments, as several hundred of these remains may be recovered from just a couple of grams of sediment. Concluding, the Chironomidae make for excellent qualitative and quantitative palaeoecological proxies for the reconstruction of past temperatures (Brooks *et al.,* 2007).

This study aims to reconstruct palaeotemperatures during the last glacial to interglacial transition using sub-fossil chironomids found within the sediments of lake Hämelsee (Lower Saxony, Germany). The results produced by this study are part of the overarching INTIMATE Example project, and will complement the variety of data produced by the project. Such data will, for example, provide additional input for climate models, allowing for the validation of simulation outcomes and the subsequent improvement of these models in predicting future global climatic change.

2. Materials and Methods

2.1 Site Description

Lake Hämelsee (52˚ 45' 34.3"N, 9˚ 18' 38.11"E; 19.5 m a.m.s.l.) is located southeast of Dörverden, in the province of Lower Saxony, Germany. The lake was originally formed as a sinkhole over Permian salt (Merkt & Müller, 1999). An alternative explanation for the formation of the lake is that it is a partially-filled pingo-remnant that formed during the end of the Weichselian (Wim Z. Hoek, pers. comm.). Currently, the lake is relatively shallow with a maximum water depth of roughly 4.95 m and it is ca. 300 x 245 m in size (Merkt & Müller, 1999). A campsite stands in the direct vicinity of the lake, surrounding it completely, while mostly agricultural landuse is observed directly outside. Merkt & Müller (1999) showed that the lake contains a complete sediment record that

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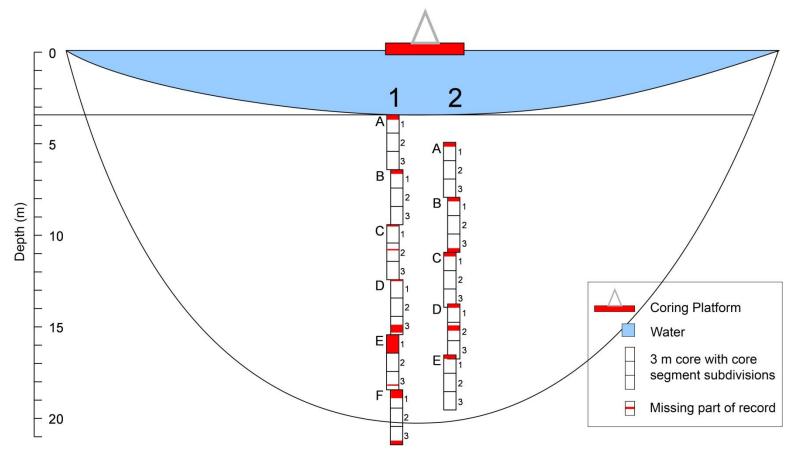
Figure 1. A coring diagram showing the length of the *HAEM13-1* (1) and *HAEM13-2* (2) cores, as well as the subdivision into core segments. (Source: Wim Z. Hoek)

spans both the Late-Glacial and the Holocene. Furthermore, the sediments are varved for part of the record, providing the opportunity to perform high-resolution analyses with a strong chronological control. Merkt & Müller's reconstructions of the environment and climate provide initial evidence for the presence of the Younger Dryas–Preboreal transition within the sediment record. In the study by Merkt & Müller (1999), this transition consisted of changes in *Cladocera* and algal abundances, which preceded the rapid development of a closed cover birch forest in a matter of decades – all indicative of a rapid warming event after the Younger Dryas period.

2.2 Core recovery and description

Two cores, *HAEM13-1* and *HAEM13-2* (figure 1), were recovered from the lake by deploying a piston corer from a floating platform near the lake's centre. Echo sounder measurements indicated that lake depths at the coring sites for *HAEM13-1* and *HAEM13-2* were 3.4 and 3.2 m, respectively. During the coring of *HAEM13-1*, siderite deposits were encountered within the sediments. These led to the loss of large parts of the Younger Dryas sequence within this core, thereby making it unsuitable for further analysis within this study. The entirety of the Younger Dryas time period was present within *HAEM13-2*, however, and this core is therefore used in the present study. Core *HAEM13-2* originally consisted of five 3-m-segments, ranging from 1.5 to 16.1 m sediment depth, which were partitioned into fifteen 1-m-segments on-site. Core segment *E2* (*HAEM13-2E2*; figure 2) contains the transition from Younger Dryas to Preboreal, and was selected for further analysis.

Core segment *HAEM-2E2* encompasses an abrupt change in organic matter content (figure 3) and sediment composition. The lower half (1495-1475 cm; 85-65 cm in figure 2) consists mostly of sandy material with low organic content, whereas the upper half (1475-

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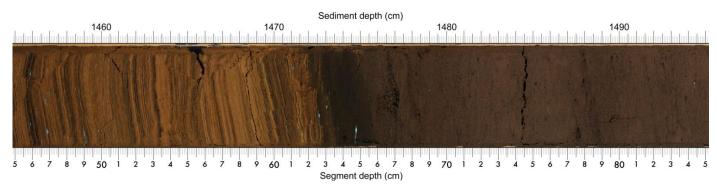
Figure 2. The segment shown here is the part of core segment *HAEM13-2E2* used in this study. Visible are the sandy sediment of part of Younger Dryas (1495-1475 cm sediment depth), the dark brown sediment representing the transition into the Holocene (1475-1473 cm sediment depth), and the varved layers of what is likely part of the Preboreal (1473-1455 cm sediment depth). (Source: Aritina Haliuc & Achim Brauer)

1455 cm; 65-45 cm in figure 2) is varved, has higher organic content, and contains a considerable amount of iron precipitates. The identification of Vedde ash at 1489-1488 cm sediment depth (Christine Lane & Gwydion Jones, pers. comm.) suggests the record starts in the Younger Dryas at roughly 11,980±80 GRIP ice core years BP. Merkt & Müller (1999) showed that the Preboreal covered roughly 920 years over 40 cm of sediment using varve counting. If this time-to-depth ratio is roughly the same for the *HAEM13-2E2* segment, this would suggest that the 20 cm of Preboreal sediments contained within the record cover roughly 460 years. Assuming the Younger Dryas-Preboreal transition took place at roughly 11,700 BP, this would indicate the entire record spans the time period of ca. 11,980 GRIP ice core years to 11.260 years BP, with a ~23 years/cm resolution for the upper 20 cm.

2.3 Sample preparation and proxy identification

The Younger Dryas–Preboreal transition most likely occurs at approximately 65 cm segment depth, where a clear change in lithology is visible. The *E2* core segment was cut into consecutive 1-cm-thick samples at the University of Potsdam, and an interval of 40 cms (45 – 85 cm segment depth) including the Younger Dryas, and the Preboreal was subsequently selected for analysis. Samples were taken from each cm of the segment, resulting in a total of 40 samples. Three samples

(1488-1487, 1476-1475 and 1473-1472 cm sediment depth) were previously used in other research, which meant that they were only available as a suspension, rather than the physical sediment itself. This is the cause of the three missing data points (figure 3), as there was nothing to be weighed. Despite this, chironomid head capsules were successfully retrieved from these suspensions.

The samples, on average 0.82 g for the lower 20 cm and 3.41 g for the top 20 cm, were treated by heating them for roughly 15 minutes on a hot plate at 150° Celsius in 10% KOH solution to deflocculate the sediment. Deflocculation of the top 20 cm took longer in most cases due to differences in sediment composition, primarily caused by the presence of iron precipitates. An appropriate amount of sediment was processed to allow for the extraction of 50 – 100 chironomid head capsules (Heiri & Lotter, 2001). The chironomid head capsules found within the sediment were generally well-preserved, and the minimum count sum of 50 individuals was easily reached in the Younger Dryas zone. However, several adjacent Preboreal samples had to be amalgamated to reach a sufficient number of head capsules (i.e. a minimum of 50), owing to the very low chironomid concentrations in the upper 20 cm (figure 5). After deflocculation of the sediments, the suspended contents were sieved through a 100 µm sieve and then transferred to a grooved Bogorov sorting tray. Chironomid head capsules, and other identifiable remains (e.g. arthropods), were

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hand-sorted at 25 x magnification and deposited on small circular cover glasses. These cover glasses were then allowed to dry, after which they were mounted onto microscope slides using Euparal© mounting medium. The identification of chironomid head capsules was based on Brooks *et al.* (2007), and the identification of *Chaoborus* mandibles was performed using the taxonomy as provided by Uutala (1990).

2.4 Statistical analysis

The resulting dataset was explored via a Principal Component Analysis (PCA) in order to identify major changes in the chironomid fauna. A rarefaction analysis was performed to estimate species richness, independent of sample sizes (Raup, 1975). Mean July air temperatures were reconstructed by applying the chironomid-temperature transfer-function as described by Brooks & Birks (2001) to the fossil dataset. This transfer-function is based on the modern distribution of 140 chironomid taxa from 153 Norwegian lakes, combined with three-component weighted averaging-partial least squares regression (WA-PLS) according to Ter Braak & Juggins (1993). Leave-one-out cross-validation was used to estimate the overall root mean square error of prediction (RMSEP), while the estimated standard errors of prediction were calculated for individual samples by performing 1000 bootstrap cycles (Birks *et al.*, 1990). This transfer-function was selected partially due to its taxonomic identification scheme, which is nearly identical to the one used in this study. The PCA and transfer-function were performed in C2 v1.7.5 (Juggins, 2007), whereas the rarefaction analysis was performed in R 3.1.0 (R Core Team, 2014) using the Vegan package (Oksanen *et al.*, 2013).

3. Results

The 2E2 core segment can be visually subdivided into two zones based on major changes visible in the chironomid assemblages. The lower 20 cm (Zone 1; 1495-1475 cm)

probably corresponds to the Younger Dryas, while the upper 20 cm (Zone 2; 1475-1455 cm) likely encompasses the start of the Holocene, the Preboreal. Overall, a total of 93 different taxa were identified from this core segment, 77 of which were chironomids (figure 5), whereas the remaining 16 belong to the non-chironomid groups (figure 6).

3.1 Chironomid assemblages

3.1.1 Zone 1 – the Younger Dryas

The Younger Dryas is primarily dominated by *Microtendipes pedellus*-type, *Sergentia coracina*-type, *Micropsectra insignilobus*-type, *Corynocera ambigua*, *Paratanytarsus penicillatus*-type, *Tanytarsus lugens*-type, and *Paratanytarsus austriacus*-type (figure 5). *M. pedellus*-type is more abundant during some periods than others, where it occasionally decreases in abundance from 20-25% to 10-15%. *M. insignilobus*-type increases at the start of zone 1 to a maximum of ~19%, but gradually decreases to ~4% at 1475 cm sediment depth. Most of the other dominant chironomid taxa maintain a relatively constant presence in zone 1, but seem to decline and disappear after the transition at 1475 cm sediment depth.

3.1.2 Zone 2 – the Preboreal

A number of other taxa now become dominant at the transition at 1475 cm sediment depth. These taxa include *Cricotopus cylindraceus*-type, *Chironomus anthracinus*-type, *Dicrotendipes nervosus*-type, *Lauterborniella*, *Pseudochironomus*, and *Ablabesmyia* (figure 5). Some of these taxa, e.g. *C. anthracinus*-type, are present in zone 1 as well, but they are less abundant there and their abundance increases after the onset of the Holocene. *M. pedellus*-type declines after the transition, but subsequently slowly increases until it reaches a peak at 1460 cm. *M. insignilobus*-type peaks soon after the transition, followed by a gradual decline over

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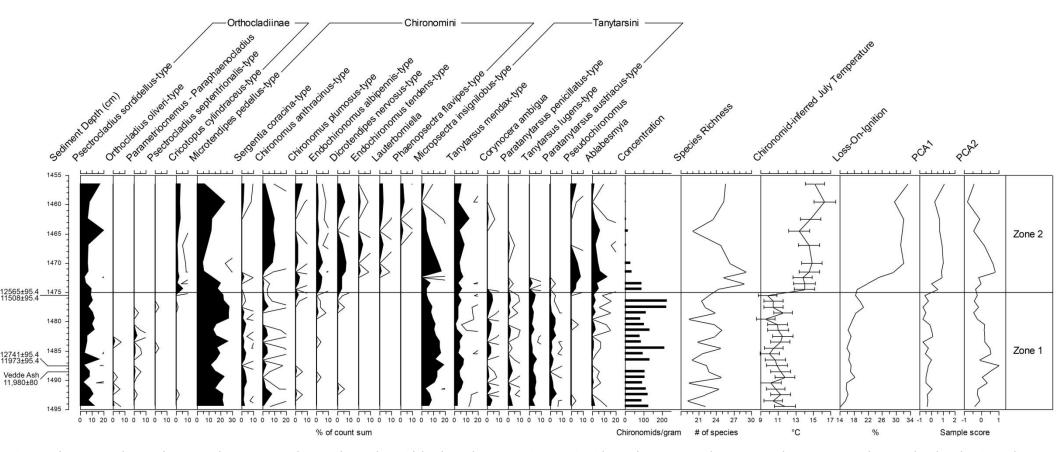
Figure 3. This summary diagram shows several representative chironomid taxa, along with head capsule concentrations, species richness, the reconstructed temperatures, loss-on-ignition and PCA results, plotted against sediment depth. Along the depth-axis, one dated ash layer along with two ^{14}C dates are shown. The horizontal line dividing the figure into two zones is the approximate location of the sedimentological transition into the Holocene. (Source Loss-On-Ignition: Wim Z. Hoek & Renée de Bruijn; Source ^{14}C dates: Marjolein Gouw-Bouman, Wim Hoek, Christine Lane, Chris Bronk Ramsey and Richard Staff)

the remainder of the record. *Pseudochironomus* abundances increase after the transition, where it reaches ~8.5% at 1473 cm sediment depth. Soon after this increase, it starts decreasing until it ultimately disappears from the record in the middle of zone 2 (~1467 cm), although it eventually returns at 1463 cm. Several other taxa maintain a relatively stable presence over both time periods, among which are *Psectrocladius sordidellus*-type, *Limnophyes-Paralimnophyes*, *Tanytarsus mendax*-type and *Procladius* (figure 5).

3.1.3 Species Richness

The rarefaction analysis of species richness applied to the chironomid data illustrated a dynamic number of species in zone 1 and 2. The number of species in zone 1 seemingly alternates between low and high amounts in a range of 19 to 25 species. The initial species richness in zone 2 is higher than that of zone 1, peaking at 29 species twice at 1474 and 1472 cm sediment depth. After these peaks, species richness decreases to 20 at 1465 cm sediment depth before increasing yet again until the end of the record, where it reaches roughly 26 species at 1456.5 cm sediment depth.

3.2 Non-chironomidae assemblages

3.2.1 Zone 1 – the Younger Dryas

The Younger Dryas period contains high amounts of *Chara* oospores, Cladocera remains, *Sialis* mandibles, *Simocephalus* ephippia, and Trichoptera remains. After the transition at 1475 cm, each of these groups declines or disappears from the environment.

3.2.2 Zone 2 – the Preboreal

Other groups, such as the *Ceratopogonidae*, mites and ostracods maintain a presence during both time periods, although a slight increase in mites is observed post-transition. The remainder of the groups, such as
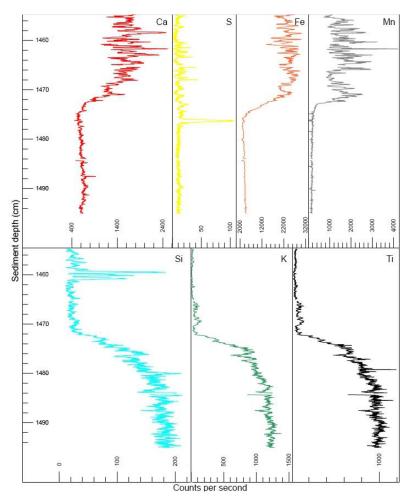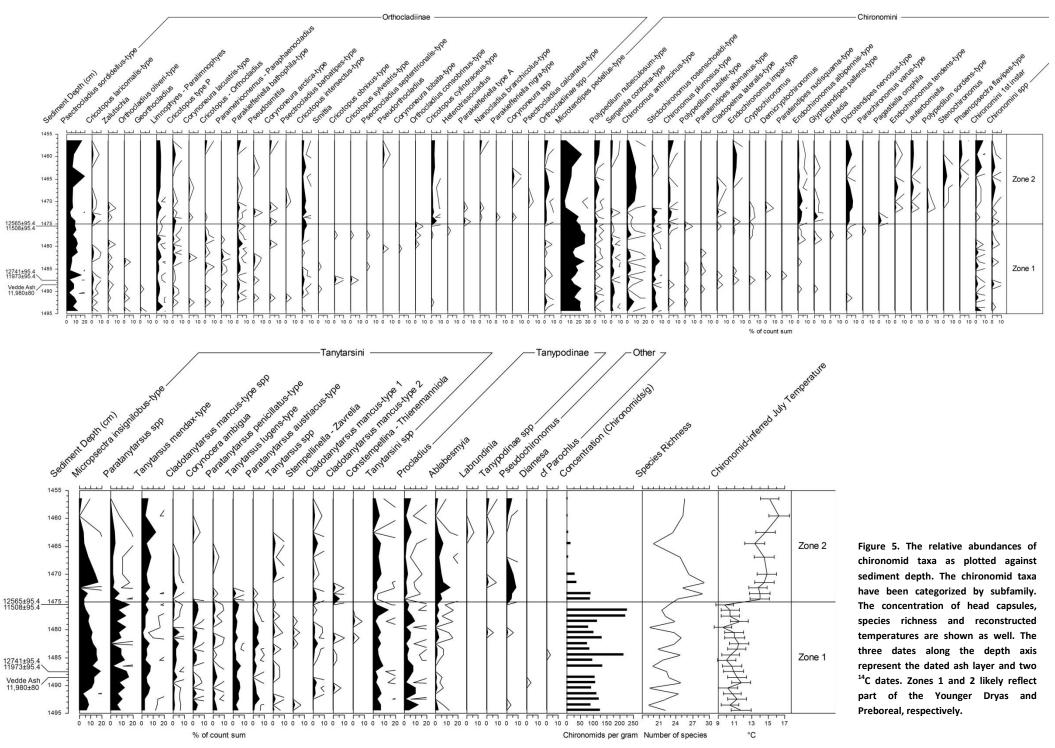

Figure 4. The X-Ray Fluorescence (XRF) results showing the presence of several important trace elements in the Hämelsee sediments, plotted against sediment depth. Displayed here are calcium (Ca), sulfur (S), iron (Fe), manganese (Mn), silicon (Si), potassium (K), and titanium (Ti). (Source: Aritina Haliuc)

Chaoborus flavicans, *Cristatella mucedo*, *Daphnia*, *Ephemenoptera*, and *Plumatella*, are absent from the Younger Dryas or occur in lower numbers, but become far more abundant during the Preboreal.

3.3 Principal Component Analysis

A Principal Component Analysis (PCA) was used to further explore (dis)similarities between samples (figure 3). The first component (*PCA1*, figure 3) shows one major change between 1477 and 1472 cm sediment depth, where the sample scores increase just after the sedimentary transition seen in the core segment (figure 2). The second component

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Figure 5. The relative abundances of chironomid taxa as plotted against sediment depth. The chironomid taxa have been categorized by subfamily. The concentration of head capsules, species richness and reconstructed temperatures are shown as well. The three dates along the depth axis represent the dated ash layer and two ^{14}C dates. Zones 1 and 2 likely reflect part of the Younger Dryas and Preboreal, respectively.

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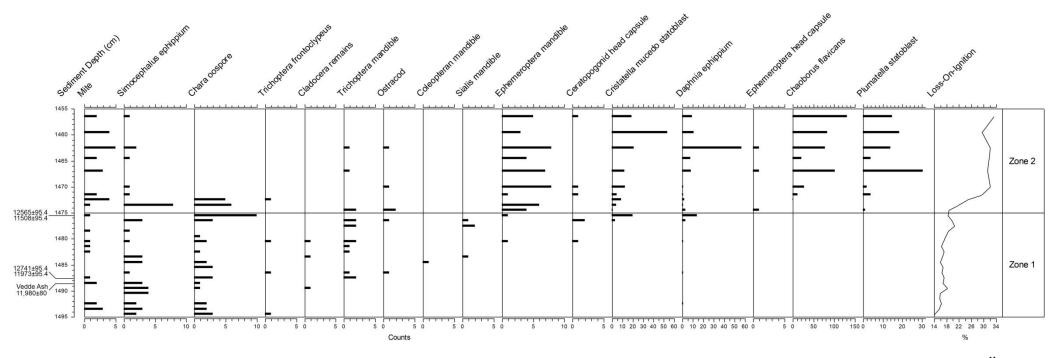
Figure 6. The counts of the identified non-chironomid taxa, as well as the loss-on-ignition, as plotted against sediment depth. The scaling of the x-axis differs between some of the taxa. One dated ash layers and two ^{14}C dates are displayed along the depth axis, which is subdivided into zones 1 and 2, which likely represent part of the Younger Dryas and Preboreal, respectively.

(*PCA2*, figure 3) is more dynamic featuring roughly four zones. Higher sample scores are observed between 1492-1484 and 1473-1467 cm, whereas lower sample scores can be found at depths of 1484-1473 and 1467-1455 cm.

3.4 Chironomid-inferred temperatures

Applying the transfer-function to the Hämelsee record using leave-one-out cross-validation led to a model with a RMSEP of 1.04 °C and a coefficient of determination (r^2) of 0.94. The reconstructed temperatures (figure 3) of zone 1 range from 9.5 to 11.8 °C and are relatively dynamic when compared to the Holocene. There seem to be several temperature fluctuations, but these all fall within the same range of temperatures as determined by the standard errors. Temperatures increase rapidly at the transition from zone1 to zone 2 by 4.2 °C from 9.8 to 14.0 °C from one sample to the other. Zone 2 temperatures range from 13.4 to 16.3 °C and warming continues until 1470 cm sediment depth, albeit at a decreased rate, where temperatures reach 14.9 °C. Slight cooling takes place at 1470-1465 cm to a temperature of 13.4 °C, after which temperatures start to rise once more until the zone 2 peak temperature (in this record) of 16.3 °C is reached. In summary, the reconstructed summer air temperatures rose from a mean of 10.8 °C in zone 1 to a mean of 14.5 °C in zone 2, with estimated standard errors ranging from 1.06 to 1.24.

4. Discussion

The *HAEM13-2E2* core segment is characterized by one large transition, as is reflected by several proxies and chironomid-derived results, including the lithology (figure 2), representative chironomid taxa (figure 3), non-chironomid taxa (figure 6), the temperature reconstruction (figure 5), Loss-On-Ignition (figure 3), and XRF data (figure 4).

4.1 Palaeoecological changes at lake Hämelsee

4.1.1 Chironomid fauna

The chironomid head capsules were mostly recovered in a good state, despite many lacking mandibles or antennal pedestals, which at times limited the taxonomic level to which they could be identified. Samples from zone 1 of the record were in a considerably better state than those of zone 2, which contained large amounts of iron. This made head capsule recovery a considerably more difficult task at times, which possibly led to damaging some head capsules due to the more intensive recovery effort.

Zone 1 contains several taxa that are absent from or barely present in zone 2. Among these are *Orthocladius oliveri*-type, *Parametriocnemus-Paraphaenocladius*, and *Psectrocladius septentrionalis*-type, which all seem to be exclusive to this timeframe. Each of the aforementioned taxa is known to live in cold lakes (table 1), as described by Brooks *et al.* (2007) and Heiri *et al.* (2011). This fits well with the cold climate prevalent during the Younger Dryas time period. A number of other taxa, such as *Sergentia coracina*-type and *Micropsectra insignilobus*-type, are most commonly observed in zone 1, but occur in zone 2 as well. These taxa prefer cold conditions (table 1), reaffirming the colder conditions during the Younger Dryas. *Paratanytarsus penicillatus*-type also occurs in the Younger Dryas sediments, although it is usually described as an indicator of warmer conditions. However, it is associated with macrophytes as well (Brooks *et al.*, 2007). Its presence here could therefore be indicative of an increased amount of macrophytes (Brooks & Heiri, 2013) or for tolerance of cool temperatures, as the temperature range of this taxon is relatively broad (table 1). In their study, Merkt & Müller (1999) have shown that macrophytes (i.e. *Batrachium*, and *Myriophyllum*) are present during the Younger Dryas and Preboreal. This evidence may therefore support the notion of the macrophyte-related presence of *P. penicillatus-*

Table 1. 22 representative chironomid taxa in alphabetic order and their temperature preferences. The temperature range is a visual approximation of first and last occurrence of certain taxa in the Swiss and/or Norwegian training sets from [a]Heiri *et al.* (2011). The temperature optimum is similar to the range, but is rather a visual approximation of where chironomid taxa become most abundant in either dataset from [a]Heiri *et al.* (2011). The column on the far right describes the temperature preference of the corresponding taxon, as stated by [b]Brooks *et al.* (2007). N/A scores indicate that no clear description was provided by Brooks *et al.* (2007).

Taxon	Temperature range[a]	Temperature optimum[a]	Ecology[b]
Ablabesmyia	8 – 20	10 – 20	Warm
Chironomus anthracinus-type	6 – 20	10 – 16	Warm
Chironomus plumosus-type	10 – 20	14 – 20	Warm
Corynocera ambigua-type	6 – 14	8 – 12	Cold
Cricotopus cylindraceus-type	6 – 16	10 – 16	Temperate
Dicrotendipes nervosus-type	8 – 20	10 – 20	Warm
Endochironomus albipennis-type	12 – 20	16 – 20	N/A
Endochironomus tendens-type	10 – 20	14 – 20	N/A
Lauterborniella	10 – 20	16 – 20	Warm
Micropsectra	4 – 20	6 – 12	Cold
Microtendipes mendax-type	8 – 20	12 – 20	Temperate
Microtendipes pedellus-type	6 – 20	10 – 16	Temperate
Orthocladius oliveri-type	4 – 16	4 – 10	N/A
Parametriocnemus – Paraphaenocladius	8 – 18	8 – 14	N/A
Paratanytarsus austriacus-type	2 – 20	2 – 10	Cold
Paratanytarsus penicillatus-type	4 – 20	10 – 14	Warm
Phaenopsectra flavipes-type	10 – 16	12 – 16	N/A
Psectrocladius septentrionalis-type	8 – 16	10 – 12	Cold
Psectrocladius sordidellus-type	4 – 20	6 – 16	Temperate
Pseudochironomus	12 – 20	14 – 20	Warm
Sergentia coracina-type	4 – 16	10 – 16	Cold
Tanytarsus lugens-type	4 - 20	4 - 12	Cold

type. However, this does not explain the absence of *P. penicillatus*-type from the Preboreal. One possibility relates to the amount of unidentified *Paratanytarsus* head capsules (*Paratanytarsus spp*) found both during the Younger Dryas and Preboreal. The lack of mandibles did not allow for further identification in these cases, which could explain the absence of *P. penicillatus* from zone 2.

There are multiple taxa that are relatively abundant throughout the entire record, such as *Microtendipes pedellus*-type, *Psectrocladius sordidellus*-type, and *Tanytarsus mendax*-type. *M. pedellus*-type, *P. sordidellus*-type, and *T. mendax*-type are known to occur in temperate lakes, and are tolerant of a broad range of temperatures (table 1), therefore their continued presence is to be expected.

The relatively high temperatures of the Preboreal are reflected by the first appearances of some taxa and the increases in others. *Endochironomus tendens*-type, *Lauterborniella* and *Phaenopsectra flavipes*-type are among the first group, which all immigrated directly after the transition into the Holocene. It is interesting to note that the temperature increase associated with the transition takes place at roughly 1475 cm sediment depth, whereas *E. tendens*-type and *Lauterborniella* first appear at 1473 cm, and *P. flavipes*-type at 1467 cm. This delayed response may be related to changes in macrophytes or trophic state, as each of these chironomids is described as having an association with macrophytes or submerged vegetation, and preferring eutrophic lakes (Brodersen *et al.*, 2001; Brooks *et al.*, 2007). Despite their late appearance, these taxa do

reflect the warmer climate of the Preboreal (table 1). *Cricotopus cylindraceus*-type, *Chironomus plumosus*-type, *Endochironomus albipennis*-type, *Dicrotendipes nervosus*-type and *Pseudochironomus* all occur sporadically throughout the Younger Dryas, but become a lot more abundant post-transition. Each of these taxa maintain presences in warm lakes (table 1) and it is therefore fitting that they are more abundant within the warmer Preboreal period. It is striking to see a decline in *D. nervosus*-type and *Pseudochironomus* at roughly 1465 cm sediment depth, which may be related to the decrease in temperatures at this point. *Chironomus anthracinus*-type and *Ablabesmyia* are relatively constantly present during the Younger Dryas, but become more abundant during the Preboreal. These findings confirm a rise in temperatures once again, as both taxa are thermophilic.

The chironomid assemblages of the Younger Dryas and Preboreal in the Hämelsee record suggest a strong increase in temperature during the Late-Glacial to Holocene transition. This is reflected by the chironomid-inferred July air temperatures as well.

4.1.2 Non-chironomids

Some non-chironomid taxa provide valuable information about past lake conditions at lake Hämelsee, such as temperature or lake depth. *Chara* oospores were found almost exclusively in the Younger Dryas zone, where they seem to indicate mostly calcareous, nutrient-poor conditions (Wehr, 2002). The XRF results (figure 4) show a strong increase in calcium after the transition into the Preboreal. This may suggest that *Chara* is absent from zone 2 due to an increase in nutrients, possibly a signal of eutrophication. Cladocera remains were found three times in zone 1, but are absent from zone 2. In the previous study by Merkt & Müller (1999), Cladoceran remains were more abundant during the Preboreal, reflecting increased temperatures. One of the possibilities is that some of these remains went unnoticed due to the iron content of zone 2

samples, or were damaged in the deflocculating process. *Chaoborus flavicans* is absent from the Younger Dryas, but becomes increasingly more abundant throughout the Preboreal. There are several problems with the use of *C. flavicans* as an environmental indicator, due to its ecological plasticity (Parma, 1969). According to Parma (1969), *C. flavicans* is typically associated with eutrophic or dystrophic water bodies, ranging from small and shallow ponds to large and deep lakes. However, he also mentions "the physico-chemical circumstances connected with the trophic situation do not seem to be essential. (…) Probably the amount of food, i.e., the zooplankton density, is of more importance." More recent studies show that the occurrence of *C. flavicans* may be positively correlated with lake depth and temperature (Luoto & Nevalainen, 2009), or negatively correlated with the oxygen content of the hypolimnion (Quinlan & Smol, 2010). Judging by a cross section of lake Hämelsee by Merkt & Müller (1999), it would seem the lake was at least 10 m deep at the time of the Preboreal. The chaoborid fauna of a deep lake is more likely to be affected by hypolimnetic oxygen than by July temperatures, where oxygen-poor conditions in the hypolimnion provide a refuge against predators (Quinlan & Smol, 2010). The increased presence of *C. flavicans* is therefore likely related to increased stratification of the lake during the summer, resulting in oxygen-poor conditions. The presence of *Cristatella mucedo* (Väliranta *et al.*, 2011) and *Plumatella* (Birks, 2000) statoblasts during the Preboreal is likely indicative of an increased nutrient status. The *Daphnia* ephippia encountered during the Preboreal are slightly more abundant than those during the Younger Dryas, this could be explained by two factors: dissolved organic matter and the rise in temperatures (Fischer *et al.*, 2011). While the previous groups all seem to indicate an increase in trophic state, the *Ephemeroptera* also become abundant during the Preboreal, despite their sensitivity to eutrophication – the reason for which they are utilized as contemporary bioindicators (Menetrey *et al.*, 2008). However, Menetrey *et*

al. (2008) also state that some species are highly resistant to eutrophication, which could provide an explanation for their abundance during the Preboreal.

The majority of recorded non-chironomid taxa seem to indicate an increase in nutrients in the lake, causing the eutrophication of the lake after the transition into the Holocene. Additionally, the increase in *Chaoborus flavicans* may reflect variations in lake depth and stratification of the lake. Merkt & Müller (1999) found algal abundances to increase after the transition into the Preboreal, possibly reflecting both the increase in temperature and the related eutrophication.

4.2 Comparison with other proxy data from lake Hämelsee

In their study of lake Hämelsee, Merkt & Müller (1999) showed that vegetation dominated by herbs and grasses occurred during the Younger Dryas, with birch becoming more widespread and juniper decreasing during the last part of this stadial. This first temperature-dependent signal leads into a rapid spread of birch, producing an almost closed forest cover within several decades. It is during this period that algae and cladocera also increase in abundance, likely as a response to increasing temperatures. This birch forest subsequently declines rapidly during the Rammelbeek cold period, which provides pine with the opportunity to become more abundant. The current study fits well with Merkt & Müller's (1999) reconstruction as reconstructed temperatures show Younger Dryas temperatures oscillating around ~11 $^{\circ}$C, followed by a 4.2 $^{\circ}$C increase at the onset of the Holocene. In zone 2, temperatures continue to rise by ca. 0.8 °C up to 1470 cm sediment depth, and subsequently decrease by almost 1.5 °C before increasing yet again. These warming and cooling events might very well correspond with the Friesland and Rammelbeek phases, which coeval with the Preboreal oscillation (Bos *et al.*, 2007; Rasmussen *et al.*, 2007) observed in the study by Merkt & Müller (1999). This cannot be

concluded with absolute certainty as a complete chronology is lacking for this study's record at the time of writing. The application of the time-to-depth ratio based on the study by Merkt & Müller (1999), however, suggests that the record lasts until roughly 11,260 BP. Rasmussen *et al.* (2007) date the end of the Preboreal oscillation to ca. 11,250 yr b2k, which which would fit well with the projected age of the record based on Merkt & Müller (1999).

Other proxies, as well as the lithology (figure 2), show similar changes occurring in the same relative timeframe, but the changes in the other proxies (i.e. LOI, XRF) have a tendency of occurring 4-5 cm above the Younger Dryas-Preboreal transition (figure 3 & 4). The species richness of the chironomid record is quick to increase following the sedimentological transition, while the concentration of chironomid head capsules seems to decrease. However, this decline in concentrations is unlikely to be of climatic origin, but rather caused by a change in sediment composition as zone 2 of the core segment contained many iron concretions. This change resulted in difficulties in finding the head capsules, as well likely being responsible for a lower overall concentration of chironomid head capsules in zone 2. Furthermore, species richness seems to follow the inferred temperatures, with lower temperatures possibly resulting in lower species richness. Loss-On-Ignition (LOI) shows an increase in organic content after the transition, similar to the results of the Principal Component Analysis (PCA), but this response is seemingly delayed. This could mean that chironomid assemblages change rapidly to adapt to the new climatic conditions, whereas other organisms (e.g. plants) lag behind, leading to the observed delayed response in LOI. Many of the elements present within the sediment (Ca, S, Fe, Mn, Si, K, Ti) change simultaneously with the LOI increase. Silicon, potassium and titanium content of the record decreases post-transition, the silicon drop possibly reflecting the lithological change associated with the end of the Younger Dryas. Merkt & Müller (1999) related an observed decrease in titanium content to lower

allochthonous input, resulting from climate conditions which largely precluded erosion and increased vegetation cover. The strong decrease in both potassium and titanium may thus be caused by lowered allochthonous influences by e.g. decreased aeolian input. Furthermore, while sulfur content remains relatively constant, increases in calcium, iron and manganese can be observed. The contrasting changes in silicon and iron may therefore represent the transition from the sandy sediments of the Younger Dryas to the iron concretion-filled sediments of the Preboreal. Interestingly, 2 of the lagging chironomid taxa (i.e. *Endochironomus tendens*-type and *Lauterborniella*) enter the record at ~1472 cm sediment depth, which corresponds with the lagging increase in Loss-On-Ignition, a peak in species richness, the increasing sample scores on both PCA components, and the changes in element concentrations. Most of these factors start changing roughly at the same depth as the transition, but stabilize or peak around ~1472 cm sediment depth. If the earlier identification of the Preboreal oscillation proofs correct, this would mean most of these factors correspond with the occurrence of the Friesland stage of the Preboreal oscillation, while the observed drop in *Endochironomus tendens*-type, *Lauterborniella*, *Phaenopsectra flavipes*-type, some other representative chironomid taxa, and species richness at ~1465 cm could correspond to the Rammelbeek cold stage.
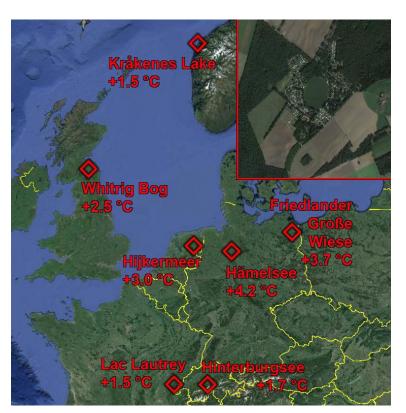
4.3 Climate change across the Younger Dryas-Preboreal boundary in northwestern Europe

Several other studies have used subfossil chironomid head capsules to study temperature change during the Late-Glacial and Holocene (Brooks & Langdon, 2014; Figure 7), which often show a similar change during the Younger Dryas-Preboreal transition, although not always of the same scale. In a study by Heiri & Millet (2005) on Lac Lautrey, France, an abrupt warming was shown to occur at the onset of the Holocene, where temperatures rose by ~1.5 ^{o}C from 14-15 to ~16.5 ^{o}C. Similar warming events were shown to occur at

Kråkenes lake, Norway, with temperatures rising from 11.5 to 12-13 ^{o}C (~1.5 ^{o}C; Brooks & Birks, 2000), and lake Hinterburgsee, Switzerland, with a temperature increase from 10.4-10.9 to 11.9-12.8 ^{o}C (~1.7 ^{o}C; Heiri *et al*., 2003). Other sites closer to lake Hämelsee show shifts in temperature more akin to those seen at the Hämelsee site (9.8 to 14 ^{o}C; ~4.2 ^{o}C), including lakes Whitrig Bog (Scotland; ~9.0 to ~11.5 ^{o}C; ~2.5 ^{o}C; Brooks & Birks, 2000), Hijkermeer (the Netherlands; ~13.5 to ~16.5 ^{o}C; ~3.0 ^{o}C; Heiri *et al.*, 2007) and Friedländer Große Wiese (Germany; ~12.0 to 15.7 ^{o}C; ~3.7 ^{o}C; Van Asch *et al.*, 2012). Temperature change at Hämelsee is nearly 2.5 °C higher than the observed change at Lac Lautrey, Kråkenes, and Hinterburgsee. The warming events seen at Hijkermeer and especially Friedländer Große Wiese are, while less intense, more similar to that of Hämelsee. Considering the inland location of lake Hämelsee and Friedländer Große Wiese, the differences in intensity may be related to the continental climate (Merkt & Müller, 1999).

5. Summary and Conclusion

The chironomid record obtained from core segment *HAEM13-2E2* likely encompasses both the end of the Late-Glacial and the onset of the Holocene, and probably spans an interval of roughly 750 years. Both the subfossil chironomid and non-chironomid remains seem to indicate warmer conditions in the upper half (zone 2), while the non-chironomid taxa also suggest eutrophication of the lake after the onset of the Holocene (zone 2). Chironomid-inferred July temperatures support the occurrence of a warming event, as temperatures in zone 1 increase from a mean temperature of 10.8 to 14.5 °C in zone 2. This rise in temperature occurs rapidly and is of roughly the same magnitude as the Younger Dryas-Preboreal transition in a nearby site (Friedländer Große Wiese; Van Asch *et al*., 2012). A comparison with other sites showed similar changes across northwest Europe, though temperature change at lake Hämelsee is strongest – likely owing to the more continental

Figure 7. A map of northwest Europe showing the location of the compared sites along with the temperature increase associated with the Younger Dryas–Preboreal transition. A local map of the Hämelsee area is shown in the topright, where the campsite and agricultural areas are clearly visible. (Images of Europe and Hämelsee area are copyrighted works of ©2014 Google and ©2009 GeoBasis-DE/BKG, image by Landsat, and country borders by US Dept of State Geographer)

climate at this site. Additionally, the combination of several proxies (e.g. chironomids, loss-on-ignition, XRF) and previous research by Merkt & Müller (1999) suggests the occurrence of both the Friesland and Rammelbeek phases of the Preboreal oscillation in this record.

In conclusion, the Late-Glacial and Holocene 750-year-record of lake Hämelsee illustrates the warming which occurred after the Younger Dryas. This is apparent from the chironomid-temperature transfer-function applied to the observed changes in the chironomid fauna, while the non-chironomid taxa primarily seem to indicate increased stratification and eutrophication of the lake at the onset of the Holocene. Lake Hämelsee has proven itself to be a useful addition to preexisting research on northwest European lakes, where it now fills one of the (knowledge)

gaps between sites such as Hijkermeer and Friedländer Groβe Wiese.

6. Acknowledgments

7. References

Birks, H.H. 2000. "Aquatic Macrophyte Vegetation Development in Kråkenes Lake, Western Norway, during the Late-Glacial and Early-Holocene." *Journal of Paleolimnology* 23 (1): 7-19.

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., and Ter Braak, C.J.F. 1990. "Diatoms and pH Reconstruction." *Philosophical Transactions of the Royal Society of London.B, Biological Sciences* 327 (1240): 263-278.

Bos, J.A.A., van Geel, B., van der Plicht, J., and Bohncke, S.J.P. 2007. "Preboreal Climate Oscillations in Europe: Wiggle-Match Dating and Synthesis of Dutch High-Resolution Multi-Proxy Records." *Quaternary Science Reviews* 26 (15): 1927-1950

Brodersen, K.P., Odgaard, B.V., Vestergaard, O., and Anderson, N.J. 2001. "Chironomid Stratigraphy in the Shallow and Eutrophic Lake Søbygaard, Denmark: Chironomid–macrophyte

co-occurrence." *Freshwater Biology* 46 (2): 253-267.

Brooks, S.J. and Birks, H.J.B. 2000. "Chironomid-Inferred Late-Glacial and Early-Holocene Mean July Air Temperatures for Kråkenes Lake, Western Norway." *Journal of Paleolimnology* 23 (1): 77-89.

Brooks, S.J. 2006. "Fossil Midges (Diptera: Chironomidae) as Palaeoclimatic Indicators for the Eurasian Region." *Quaternary Science Reviews* 25 (15): 1894-1910.

Brooks, S.J. and Birks, H.J.B. 2001. "Chironomid-Inferred Air Temperatures from Lateglacial and Holocene Sites in North-West Europe: Progress and Problems." *Quaternary Science Reviews* 20 (16): 1723-1741.

Brooks, S.J. and Birks, H.J.B. 2000. "Chironomid-inferred Late-glacial Air Temperatures at Whitrig Bog, Southeast Scotland." *Journal of Quaternary Science* 15 (8): 759-764.

Brooks, S.J. and Heiri, O. 2013. "Response of Chironomid Assemblages to Environmental Change during the Early Late-Glacial at Gerzensee, Switzerland." *Palaeogeography, Palaeoclimatology, Palaeoecology* 391: 90-98.

Brooks, S.J., Langdon, P.G., and Heiri, O. 2007. *The Identification and use of Palaearctic Chironomidae Larvae in Palaeoecology*. Quaternary Research Association, Great Britain.

Fischer, J.M., Olson, M.H., Williamson, C.E., Everhart, J.C., Hogan, P.J., Mack, J.A., et al. 2011. "Implications of Climate Change for Daphnia in Alpine Lakes: Predictions from Long-Term Dynamics, Spatial Distribution, and a Short-Term Experiment." *Hydrobiologia* 676 (1): 263-277.

Heiri, O., Brooks, S.J., Birks H.J.B., and Lotter, A.F. 2011. "A 274-Lake Calibration Data-Set and Inference Model for Chironomid-Based Summer Air Temperature Reconstruction in Europe." *Quaternary Science Reviews* 30 (23): 3445-3456.

Heiri, O., Cremer, O., Engels, S., Hoek, W.Z., Peeters, W., and Lotter, A.F. 2007. "Lateglacial Summer Temperatures in the Northwest European Lowlands: A Chironomid Record from Hijkermeer, the Netherlands." *Quaternary Science Reviews* 26 (19): 2420-2437.

Heiri, O., and Lotter, A.F. 2001. "Effect of Low Count Sums on Quantitative Environmental Reconstructions: An Example using Subfossil Chironomids." *Journal of Paleolimnology* 26 (3): 343-350.

Heiri, O., Lotter, A.F., Hausmann, S., and Kienast, F. 2003. "A Chironomid-Based Holocene Summer Air Temperature Reconstruction from the Swiss Alps." *The Holocene* 13 (4): 477-484.

Heiri, O. and Millet, L. 2005. "Reconstruction of Late Glacial Summer Temperatures from Chironomid Assemblages in Lac Lautrey (Jura, France)." *Journal of Quaternary Science* 20 (1): 33-44.

Hoek, W.Z. 1997. "Late-Glacial and Early Holocene Climatic Events and Chronology of Vegetation Development in the Netherlands." *Vegetation History and Archaeobotany* 6 (4): 197-213.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Juggins, S. 2007. "C2 Version 1.5: Software for Ecological and Palaeoecological Data Analysis and Visualisation." *University of Newcastle, Newcastle upon Tyne*.

Luoto, T.P., and Nevalainen, L. 2009. "Larval Chaoborid Mandibles in Surface Sediments of Small Shallow Lakes in

Finland: Implications for Palaeolimnology." *Hydrobiologia* 631 (1): 185-195.

Menetrey, N., Oertli, B., Sartori, M., Wagner, A., and Lachavanne, J.B. 2008. "Eutrophication: Are Mayflies (Ephemeroptera) Good Bioindicators for Ponds?" *Hydrobiologia* 597 (1): 125-135.

Merkt, J. and Müller, H. 1999. "Varve Chronology and Palynology of the Lateglacial in Northwest Germany from Lacustrine Sediments of Hämelsee in Lower Saxony." *Quaternary International* 61 (1): 41-59.

Mortensen, A.K., Bigler, M., Grönvold, K., Steffensen, J.P., Johnsen, S.J. 2005. "Volcanic Ash Layers from the Last Glacial Termination in the NGRIP Ice Core." *Journal of Quaterny Science* 20 (3): 209-219.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., et al. 2013. Vegan: Community Ecology Package. R package version 2.0-10. URL: http://CRAN.R-project.org/package=vegan/.

Parma, S. 1969. "Notes on the Larval Taxonomy, Ecology, and Distribution of the Dutch Chaoborus Species (Diptera, Chaoboridae)." *Beaufortia*.

Quinlan, R., and Smol, J.P. 2010. "Use of Subfossil Chaoborus Mandibles in Models for Inferring Past Hypolimnetic Oxygen." *Journal of Paleolimnology* 44 (1): 43-50.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., et al. 2006. "A New Greenland Ice Core Chronology for the Last Glacial Termination." *Journal of Geophysical Research: Atmospheres (1984–2012)* 111 (D6).

Rasmussen, S.O., Vinther, B.M., Clausen, H.B., and Andersen, K.K. 2007. "Early Holocene Climate Oscillations Recorded in Three Greenland Ice Cores." *Quaternary Science Reviews* 26 (15): 1907-1914

Raup, D.M. 1975. "Taxonomic Diversity Estimation using Rarefaction." *Paleobiology*: 333-342.

ter Braak, C.J.F. and Juggins, S. 1993. "Weighted Averaging Partial Least Squares Regression (WA-PLS): An Improved Method for Reconstructing Environmental Variables from Species Assemblages." *Hydrobiologia* 269 (1): 485-502.

Uutala, A.J. 1990. "Chaoborus (Diptera: Chaoboridae) mandibles—paleolimnological Indicators of the Historical Status of Fish Populations in Acid-Sensitive Lakes." *Journal of Paleolimnology* 4 (2): 139-151.

Väliranta, M., Weckström, J., Siitonen, S., Seppä, H., Alkio, J., Juutinen, S., and Tuittila, E. 2011. "Holocene Aquatic Ecosystem Change in the Boreal Vegetation Zone of Northern Finland." *Journal of Paleolimnology* 45 (3): 339-352.

van Asch, N., Kloos, M.E., Heiri, O., de Klerk, P., and Hoek, W.Z. 2012. "The Younger Dryas Cooling in Northeast Germany: Summer Temperature and Environmental Changes in the Friedländer Groβe Wiese Region." *Journal of Quaternary Science* 27 (5): 531-543.

Wehr, J.D. 2002. *Freshwater Algae of North America: Ecology and Classification*. Retrieved from http://books.google.com/.