Anthropogenic versus climatic control in a high-resolution 1500-year chironomid stratigraphy from a southwestern Greenland lake

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ABSTRACT

We performed a high-resolution study of chironomid assemblages in a sediment core retrieved from Lake Igaliku in southern Greenland. The well-dated core is located within the former Norse Eastern Settlement and covered the last 1500 yr. The comparison of chironomid stratigraphy (PCA axis scores) with instrumental temperature data, land use history and organic matter in the sediment over the last 140 yr suggested that the primary changes in chironomid fauna in 1988 ± 2 yr were driven by the shift to modern agriculture in the catchment. This unprecedented change in chironomid fauna was most likely triggered by a shift in in-lake processes. Within the instrumental period, subtle variations in the chironomid assemblages that occurred before 1988 ± 2 yr were significantly correlated with summer temperatures even in times of traditional extensive sheep farming in the catchment. The relevance of the chironomid-derived climate signal over the last 1500 yr was supported by its good concordance with previous studies in west Greenland and in the Arctic. The chironomid assemblage therefore appeared to be a valuable proxy for climate changes within the Norse colony area. Synchronous changes in Norse diet and chironomid-reconstructed climate give new insights into the interplay of Norse society with climate.

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Introduction

In light of the need for a better understanding of the interactions between human societies and their environment in the current context of global change, South Greenland appears to be an unrivaled open-air laboratory, characterized by a unique history of human–environment relationships. At the end of the 10th century, the Norse colonized the agriculture-free areas in the Eastern Settlement (~61°N), and somewhat later, the Western Settlement (~64°N) (Gad, 1970). The rhythm (collapse or progressive demise) and the causalities of the abandonment during the 15th century remain a matter of debate (Dugmore et al., 2012; Massa et al., 2012a). The Norse most likely failed to cope with a complex interplay of the unpredictable climate and environmental changes of the Little Ice Age and socio-economic conjunctures (Dugmore et al., 2012). Approximately five hundred years later, spurred on by Denmark, agriculture resumed in southern Greenland at the beginning of the 20th century.

The land-use effects on the local environment of the Norse Eastern Settlement have been demonstrated by archeological surveys (Dugmore et al., 2005) and by multi-proxy studies of natural archives such as lake sediments (Fredskild, 1978; Massa et al., 2012a) soil or peat records (Ledger et al., 2013). In contrast, changes in the local climate over the last 1500 years are still sparsely documented by only a few records. The available datasets include the well-known records

from the Greenland ice sheet, with the closest one (Dye-3) lying more than 400 km from the Eastern and Western settlements, several paleoceanographic studies performed along the West Greenland Shelf (Lassen et al., 2004), and lacustrine records in which the period of interest was studied at low resolution (Axford et al., 2013). To date, no continental record of climate change for the last 1500 yr is available within the Norse colony area.

In lakes, chironomid larvae are benthic organisms that produce chitinous remains (head capsules) during their development. Past changes in communities are reconstructed after extraction and identification of head capsules preserved in the sediment. Temperature was identified as one of the key factors controlling chironomid assemblage distribution at a large geographical scale (Eggermont and Heiri, 2012; Walker and Cwynar, 2006). Accordingly, chironomid assemblages are widely considered to be a valuable climate proxy in the sediment record (Walker and Cwynar, 2006). Chironomids have been successfully used as quantitative paleoclimatic indicators in arctic lakes (e.g., in Iceland: Axford et al., 2008; Langdon et al., 2011; in arctic Canada: Porinchu et al., 2009; Medeiros et al., 2012; and on Baffin Island: Thomas et al., 2011). Nevertheless, chironomid assemblages are potentially affected by a variety of environmental conditions interacting in complex ecological processes (Brodersen and Quinlan, 2006; Eggermont and Heiri, 2012; Velle et al., 2010). In addition to temperature, the most commonly recognized influencing factors are trophic status (Brooks et al., 2001), oxygen conditions (Quinlan and Smol, 2001), organic matter in the sediment (Verneaux and Aleya, 1998) and salinity (Eggermont et al., 2006). Therefore, in times of low-amplitude temperature changes, the

influence of temperature may be outmatched by the influence of other environmental factors on the chironomid response. In southwestern Greenland, the study of the modern distribution of chironomids by Brodersen and Anderson (2002) showed that both climate (temperature) and in-lake processes (trophic state) were possible interacting forcing factors for the chironomid community.

The main objective of this paper is to assess the ability of chironomid assemblages to track climate change within the Norse Eastern Settlement area. Therefore, chironomid assemblages and the organic matter accumulation rate were analyzed at a high resolution in a sediment core from Lake Igaliku that has been extensively studied for pollen (Gauthier et al., 2010), diatoms (Perren et al., 2012) and sedimentology (Massa et al., 2012a). We aim to (1) reconstruct the changes in the chironomid assemblages during the last 1500 yr; (2) decipher the respective influence of human-induced and climate-induced (i.e., summer temperature) changes on the chironomid fauna; (3) assess the reliability of the possible chironomid-derived climate record; and (4) if relevant, provide new insights into the relationship between the Norse society and local climate changes.

Study site

Settings

Lake Igaliku (61°00′N, 45°26′W, 15 m asl) is a small lake located in southern Greenland (Fig. 1). It occupies a low valley between the head of Igalikup Kangerlua (Igaliku fjord) and Tunulliarfik fjord (Erik's fjord), at ca. 2 km northwest of the present-day town of Igaliku. The lake has a surface area of 34 ha and a maximum depth of 26 m (Fig. 1). Water drains into the lake from a relatively low relief catchment (maximum altitude of 300 m asl) of 3.1 km^2. A small outlet on the northern shore drains into the Tunulliarfik fjord. The basement rocks are primarily Ketilidian Julianehåb granite (Allaart, 1976), unconformably overlain

by sandstones and lavas, all forming the Eriksfjord formation (Poulsen, 1964).

The study area is characterized by a subcontinental, subarctic climate. The meteorological station at Narsarsuaq (17 km north of the lake, Fig. 1) has a mean annual temperature of 0.9°C, with a maximum in July of 10–11°C, 194.8 days/yr with frost and annual precipitation of 615 mm (Cappelen et al., 2001).

Land-use history

Igaliku lies at the very location of the medieval settlement of Garðar in the center of the former Eastern Settlement. The area was settled soon after the Landnám, and Garðar is believed to have been the residence of the daughter of Erik the Red. Garðar was most likely the most important place in the Eastern Settlement as it became the Bishop seat as well as a probable Greenlandic assembly site (Jones, 1986; Sanmark, 2009). The high status of Garðar has been further supported by archeological fieldwork. Fifty-two Norse structures have been recognized, including byre–barn complexes, livestock pens, goat and sheepfolds and an irrigation system (Nørlund and Roussell, 1929). The catchment of Lake Igaliku was most likely used as extensively grazed grassland. Indeed, pollen and coprophilous fungi from the Igaliku lake sediment showed initial land clearance and the presence of grazing livestock around the lake in the 10th century (Gauthier et al., 2010). Sedimentary evidence for grazing pressure in the lake catchment culminated in the 12–13th century, resulting in soil erosion rates twice as great as the pre-Landnám background (Massa et al., 2012a). The Norse colonization phase is then followed by a decrease in anthropogenic indicators starting in the early 14th century and their subsequent disappearance in the 14th–15th century (Gauthier et al., 2010; Massa et al., 2012a).

Present-day Igaliku was founded at the end of the 18th century. Agriculture in the area resumed in the 1920s under the incentive of the Danish Government and consists primarily of sheep farming with
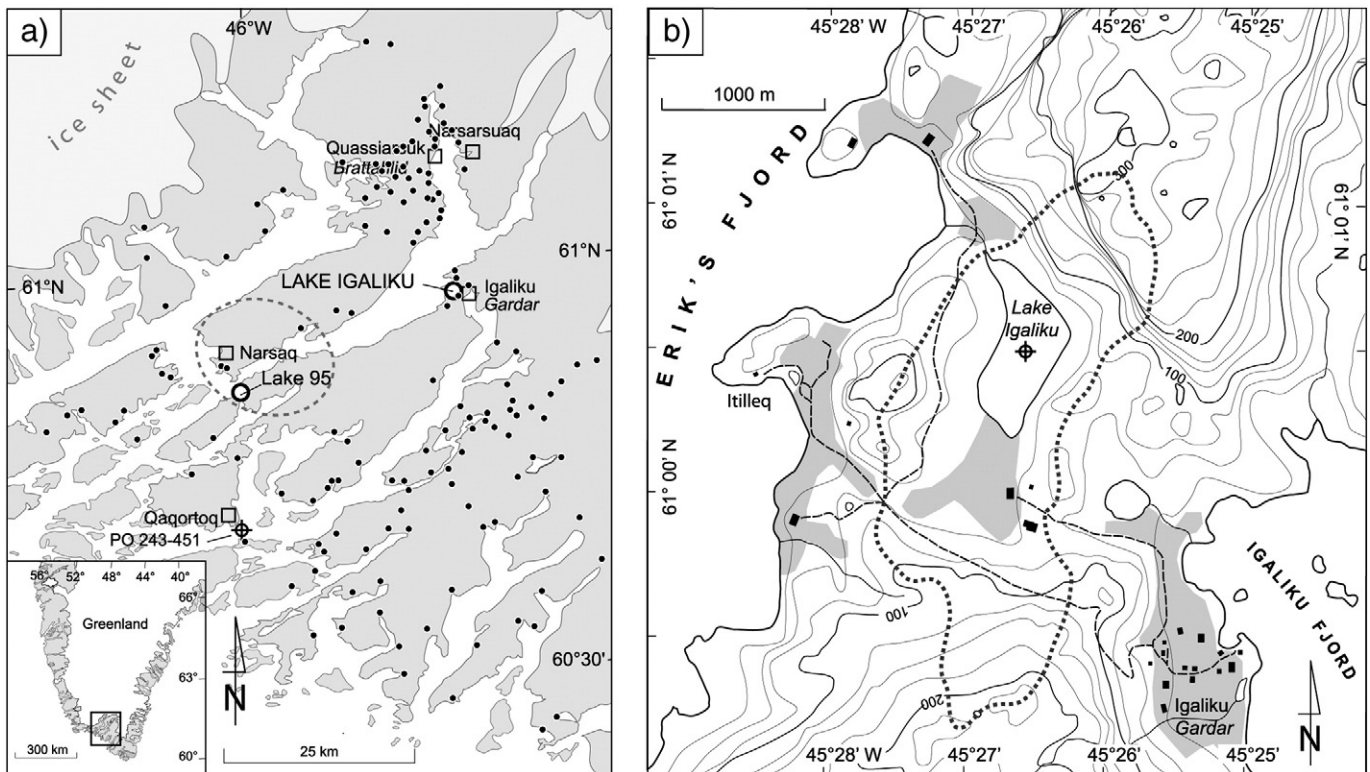

Figure 1. Location map of the study area in southwestern Greenland. a) Map of the Eastern settlement showing the location of Lake Igaliku (this study), Lake 95 (Lindegaard and Mæhl, 1992), the study area of Lindegaard et al. (1978), core PO 243–451 in outer Igaliku Fjord (Jensen et al., 2004; Lassen et al., 2004) and the Norse ruin groups (black dots). b) Map of the local environment of Lake Igaliku indicating buildings (black rectangles), current hay fields (shaded area), the archeological site of Garðar and the catchment limits (dotted line).

a few attempts at raising cattle. Farming was first based on extensive grazing with limited supplements of fodder during winter; it could be considered to be an analog for Norse agriculture (Perren et al., 2012). During the 1980s, to reduce the inherent hazards of the Greenland climate, the sheep management shifted to a new mode, with stabling during the seven months of the Greenland winters. This implied the supply of a considerable amount of fodder, leading to the development of hay-field development and the large use of fertilizers. Modernly, there are two farms in the catchment area of Lake Igaliku. Several hundred sheep freely graze in the surrounding area during summer. The south and north shores of the lakes are cultivated to produce winter fodder. Although Norse agriculture only induced subtle changes in the Lake Igaliku diatom flora, modern farming and consecutive nutrient enrichment in the lake, most likely in combination with post-1920s climate warming, has led to drastic changes in the lake ecosystem as suggested by marked shifts in diatoms, scaled chrysophytes and $\delta^{15}N$ (Perren et al., 2012).

Methods

Coring

In 2007, a suite of sediment cores was retrieved from the deepest part of the lake using UWITEC gravity and piston corers (63 mm in diameter). The composite 4-m-long core was constructed from magnetic susceptibility and gamma density profiles acquired at a high resolution (5-mm interval) using a Geotek Multi-Sensor Core device. The sediment record covers the last 10,000 yr (Massa et al., 2012b). This study focuses on the upper part of the sequence spanning the last 1500 yr.

Chronology

The core chronology (Fig. 2) is based on (i) 13 AMS radiocarbon dates, (ii) a 20-sample ^{137}Cs profile measuring the maximum fallout following atmospheric nuclear weapon tests (AD 1963), and (iii) 14 α-spectrometry ^{210}Pb measurements processed with a constant rate of supply model (Appleby and Oldfield, 1978). Radiocarbon dates were performed by the Poznan Radiocarbon Laboratory and the University Claude Bernard, Lyon, and calibrated using the current northern hemisphere ^{14}C calibration dataset, Intcal09 (Reimer et al., 2009). The age–depth model, combining short-lived radionuclide measurements

and radiocarbon dates, was then built using a cubic smooth spline function following Blaauw (2010). The detailed method used for the Lake Igaliku sedimentary chronology was reported by Massa et al. (2012a, 2012b).

Sampling and analysis

Chironomid assemblages, organic matter elemental analysis (C, N) and total organic carbon fluxes were determined from 104 contiguous samples. Sample thickness was 0.5 cm for the 10 uppermost cm and was thereafter individually adjusted (0.5–1 cm) to match changes in the sedimentological characteristics (visible laminae). According to the age–depth model, this sampling strategy led to a mean time resolution of 14 yr per sample (between 2 and 31 yr per sample).

Chironomid head capsules (HC) were extracted from the sediment following the standard procedure including KOH (10%) treatment and sieving at 100 and 200 μm. Chironomid remains were hand-sorted from the sieving residue under 40 to 70× magnification. HC were mounted ventral side up on microscope slides using Aquatex© mounting agent. Identification of the specimens to the genus- or species/ group-level primarily followed Wiederholm (1983) and Brooks et al. (2007) and was performed under 100 to 1000× magnification. The relative abundance of each taxon as a percentage of the total number of specimens was calculated for each sample. Only taxa occurring in at least two samples, with a maximum relative abundance of greater than 2%, were included for further analysis. Stratigraphic diagrams of the relative abundance of the chironomid taxa were performed using TGView v. 2.0.2 (Grimm, 2004). The chironomid assemblage zones were defined from a stratigraphically constrained cluster analysis performed by Coniss (Grimm, 2004). The number of statistically different biozones was assessed using the broken stick model. Ordinations (Principal Component Analysis, PCA) was performed using the Vegan packages for R (Oksanen et al., 2011). Prior to the PCA, we applied a square root transformation to the percentage data to reduce difference between smallest non-zero percentages and largest percentages and to optimize the 'signal' to 'noise' ratio in the data.

Prior to the analysis for organic matter content, the samples were gently dried at 60°C until reaching constant weight, and water content (WC) was calculated from the weight loss. The total organic carbon (TOC) and nitrogen concentrations were determined for the 104 samples using a vario MAX CNS analyzer (Elementar) from ca. 170 mg of dried sediment (see Massa et al., 2012a). The C/N atomic ratio was calculated for each of the 104 samples. TOC percentages were transformed to organic C accumulation rate ($C_{org}AR$ in $mg \cdot cm^{-2} \cdot yr^{-1}$) from the sediment accumulation rate (SAR) derived from the age/depth modeling using the formula:

$$C_{org}AR = WBD \cdot (1 - WC) \cdot TOC \cdot SAR$$

where WBD is the wet bulk density (mg/cm^3).

Results

Chironomid analysis

Among the 104 analyzed samples, the head capsule counts ranged from 11 to 103, with a mean of 45 HC per sample (Fig. 3). Due to the small amount of available sediment, less than 20 HC could be retrieved in 4 samples (Fig. 3). A total of 32 different taxa were identified in the Igaliku record, and 27 of them met the minimum frequency criteria and were included in further analyses.

Throughout the entire record, the chironomid assemblages are highly dominated by *Heterotrissocladius subpilosus*-type and *Micropsectra insignilobus*-type. Other taxa, such as *Dicrotendipes*, *Psectrocladius sordidellus*-type, *Heterotrissocladius marcidus*, *Chironomus anthracinus*-type and *Corynoneura arctica*-type, are present in all samples with lower relative abundance.
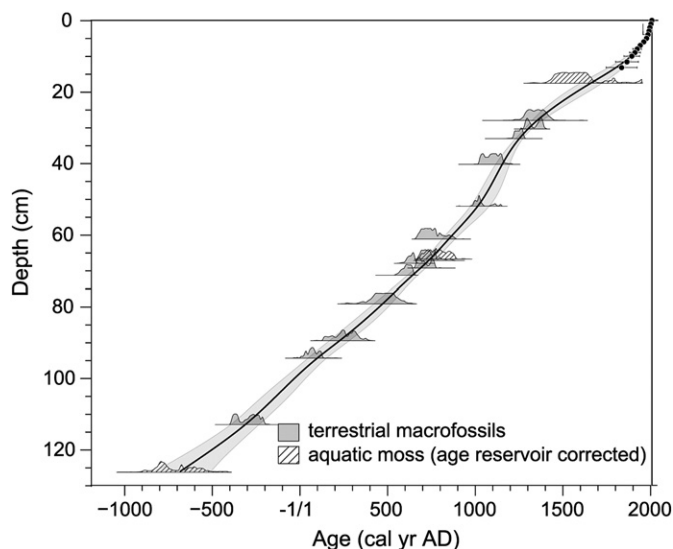

Figure 2. Age/depth model of the Lake Igaliku sediment record with ^{210}Pb age estimates (black dots) and probability distribution curves of calibrated ^{14}C ages (Massa et al., 2012a, 2012b).
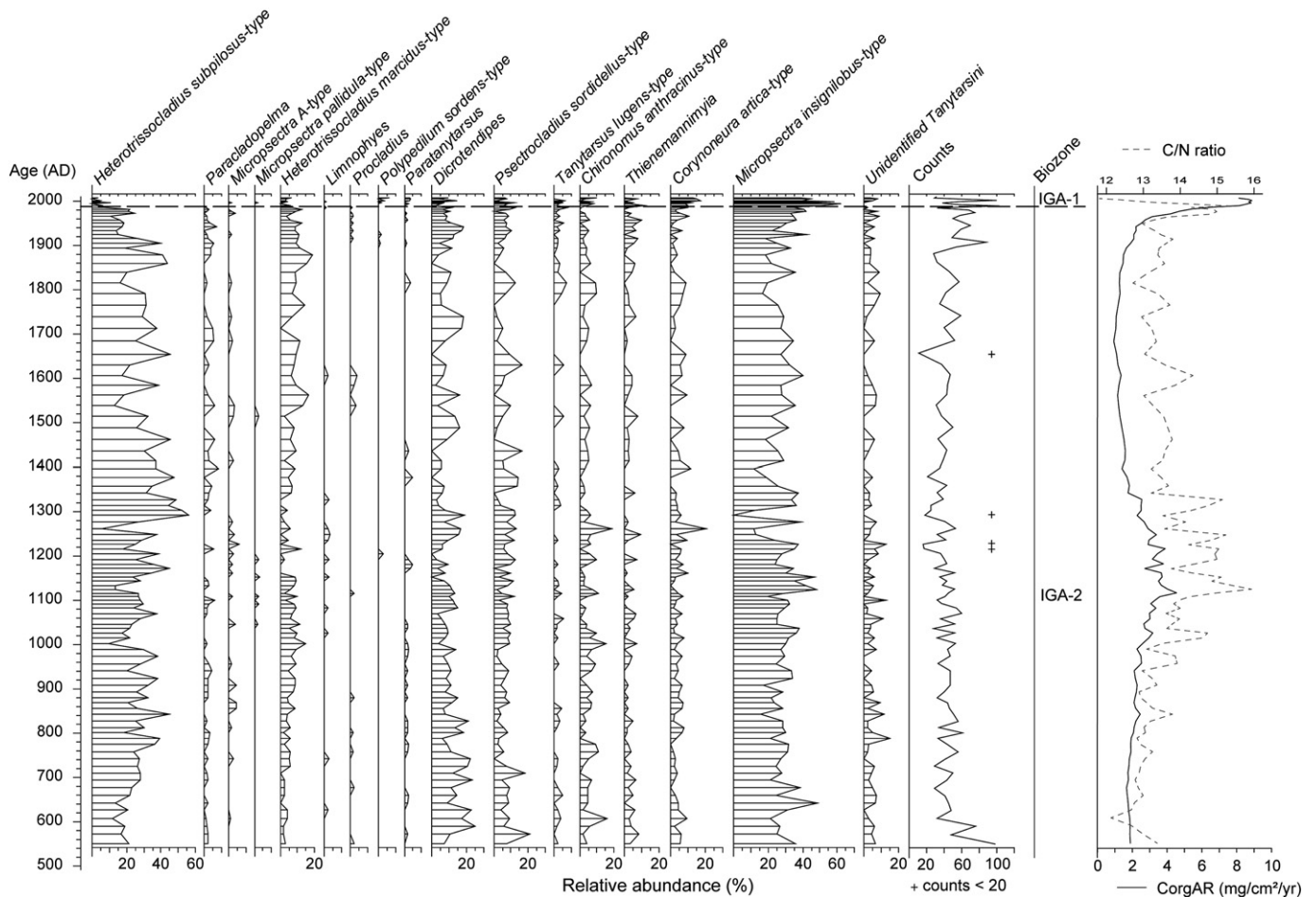
Figure 3. Percentage diagram of the most common chironomid taxa and changes in the organic carbon accumulation rate ($C_{org}AR$) and in the carbon:nitrogen ratio (C/N). +: samples with counts less than 20 head capsules. The dotted line indicates the limits of the chironomid biozones from the cluster analysis CONISS.

Two statistically significant biozones (IGA-1 and IGA-2) were recognized within the Igaliku chironomid stratigraphy from the cluster analysis (Fig. 3). IGA-1 is composed of the seven uppermost samples (3.5 cm) of the sediment record. It spans a short time period between ca. AD 1988 and 2007. IGA-2 is composed of the 97 remaining samples taken between 3.5 and 76 cm depth and covering the AD 540–1988 time window.

To unravel the taxa involved in the primary shift in the chironomid community between IGA-1 and 2 and to depict the more subtle changes
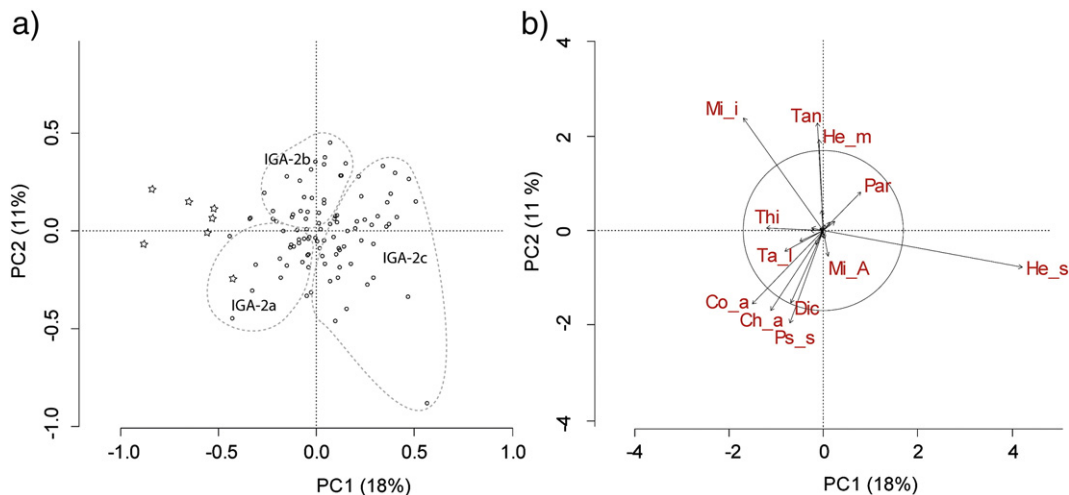

Figure 4. PCA₁ biplot of (a) the sediment core sample (dots: samples belonging to IGA-2, stars: samples belonging to IGA-1) and (b) the chironomid taxa (arrows). The three sub-groups of IGA-2 (IGA-2a to IGA-2c) and the circle of equilibrium contribution of the PCA₁ are indicated. Taxa that have vectors longer than the radius of the circle make a higher contribution than average and may be considered for interpretations. Only the 12 taxa with the longest vector are indicated. Ch_a: *Chironomus anthracinus*-type, Co_a: *Corynoneura arctica*-type, Dic: *Dicrotendipes*, He_m: *Heterotrissocladius marcidus*-type, He_s: *Heterotrissocladius subpilosus*-type, Mi_i: *Micropsectra insignilobus*-type, Mi_a: *Micropsectra* type A, Par: *Paracladopelma*, Ps_s: *Psectrocladius sordidellus*-type, Tan: *Tanytarsus* spp., Ta_l: *Tanytarsus lugens*-type, Thi: *Thienemannimyia*.

that occurred during the IGA-2 biozone, a first principal component analysis (PCA$_1$) was performed from the sample/taxa matrix (104 samples, 27 taxa).

The PCA$_1$ biplot (Fig. 4) showed two main groups of samples that correspond to the biozones determined from the cluster analysis. The seven samples of biozone IGA-1 are pooled at the negative end of axis one of the PCA$_1$ (Fig. 4). This group differs from the samples of IGA-2 by a combination of high relative abundance of *M. insignilobus*-type (ca. 45%) and *C. arctica*-type (15%) and very low percentages of *H. subpilosus*-type (5%) (Fig. 3). Samples of IGA-2 are characterized by higher relative abundance of *H. subpilosus*-type (from 12 to 50%) and feature higher scores along axis 1 (Figs. 3 and 4). This group of samples can be further tentatively divided into sub-groups according to their projection on the PCA$_1$ biplot. From low to high scores along axis 1, three sub-groups of samples may be identified. The first set of samples (IGA-2a) is found at negative scores along both axes 1 and 2. These samples are marked by the taxonomic association among *P. sordidellus*-type, *C. arctica*-type, *C. anthracinus*-type and *Dicrotendipes* (Fig. 4). The second sub-group of samples (IGA-2b) features high relative abundance of *M. insignilobus*-type and *H. marcidus*-type. These samples are plotted at the positive side of axis 2 and near the origin of axis 1. The third sub-group of samples (IGA-2c) is found at positive scores along axis 1 and is characterized by the highest relative abundance of *H. subpilosus*-type for the whole record (up to 50%).

Samples from IGA-1 were removed from the data set, and a second PCA (PCA$_2$) was performed from the new samples/taxa matrix (97 samples, 27 taxa). The projection of the samples in the PCA$_2$ biplot (not shown) was closely similar to the PCA$_1$. It led to the identification of the same 3 sub-groups of samples (from IGA-2a to IGA-2c) with identical characteristic taxa than suggested by the PCA$_1$.

OM records

From the beginning of the record to ca. AD 1000, the accumulation rate of organic matter and the C/N molar ratios were steady, with mean values of 2 mg·cm^{-2}·yr^{-1} and 11, respectively (Fig. 3). Between ca. AD 1000 and 1330, the mean values of C$_{org}$AR and the C/N ratio increased up to 3.5 mg·cm^{-2}·yr^{-1} and 14.6, respectively. C$_{org}$AR featured a dome-shaped curve with higher values found during the AD 1120–1220 interval. At ca. AD 1330, C$_{org}$AR and C/N decreased and remained thereafter at lower values, i.e., 1.5 mg·cm^{-2}·yr^{-1} and 13.4, respectively. Following a sharp rise in ca. AD 1970, C$_{org}$Ar reached its maximum values (8 mg·cm^{-2}·yr^{-1}) between ca. AD 1990 and 2007. The C/N ratio also increased following ca. AD 1970, but it sharply declined after ca. AD 1990 to reach its lowest value for the whole record in 2007 (i.e., 10).

Discussion

Lake Igaliku chironomid ecology

The taxa found in the sediment samples of Lake Igaliku are typical for lakes from southwest Greenland (Brodersen and Anderson, 2002; Lindegaard and Mæhl, 1992; Lindegaard et al., 1978). The strong dominance of *Heterotrissocladius* spp. and *M. insignilobus*-type observed at Lake Igaliku was found to be characteristic for cold, large, deep, oligotrophic lakes in the set of 47 lakes studied by Brodersen and Anderson (2002) in the Sisimiut-kangerlussaq region. Lindegaard et al. (1978) found that a large population of *Micropsectra* was typical of the faunal composition in the 17 studied lakes in the Narsaq Area (Fig. 1). Furthermore, *Heterotrissocladius oliveri*, a member of the *Subpilosus*-group (Saether, 1975), was primarily collected in the deepest lakes, with maximum depths between 18 and 65 m (Lindegaard et al., 1978).

A major ecological shift at AD 1988

The main shift in the chironomid record occurred at the IGA-1/IGA-2 transition (ca. AD 1988 $\pm$ 2 yr) and was characterized by a sharp drop in *H. subpilosus*-type and the converse increase in the percentages of *M. insignilobus*-type and *C. arctica*-type during IGA-1. The *H. subpilosus*-group includes strongly cold stenothermic and ultraoligotrophic species (Saether, 1975). In several chironomid temperature calibration datasets, *H. subpilosus*-type is reported as one of the coldest indicators (Larocque et al., 2001, 2006), although it can occur in lakes at the warm end of the temperature gradient. According to the distribution of subfossil material in the surface sediment in southwestern Greenland, *H. subpilosus*-type features both low trophic (TN) and surface water temperature optima (Brodersen and Anderson, 2002). In many temperature calibration datasets, *M. insignilobus*-type and *C. arctica*-type are more widely distributed along the temperature gradient and feature higher temperature optima (Heiri et al., 2011; Larocque et al., 2001). *M. insignilobus*-type is also typical for the profundal zone of deep lowland oligotrophic lakes (in Millet et al. (2010) = *Micropsectra contracta*-type). In lakes from southwestern Greenland, *M. insignilobus*-type has intermediate trophic and temperature optima, whereas *C. arctica*-type exhibits even higher optima (Brodersen and Anderson, 2002). Finally, the modern distribution data and ecology of the taxa suggest that both climate (temperature) and in-lake processes (trophic functioning) are possible interacting forcing factors of the primary shift that occurred in the chironomid community, i.e., the IGA-1/IGA-2 transition.

Subtle ecological variations before AD 1988

Slight changes in the chironomid assemblages within IGA-2 are suggested by the PCA$_1$ biplot (Fig. 4). The first sub-set of samples (IGA-2a) is plotted at negative values along PCA$_1$ axis 1 and is characterized by the taxa (i.e., *P. sordidellus*-type, *C. arctica*-type, *C. anthracinus*-type and *Dicrotendipes*) with the highest trophic and temperature optima for the Lake Igaliku record, with reference to the modern distribution of chironomid taxa in lakes of southwestern Greenland (Brodersen and Anderson, 2002). *Dicrotendipes* were found only in lowland lakes in a modern calibration dataset from northern Sweden (Larocque et al., 2001). *Psectrocladius*, *Dicrotendipes* and *C. anthracinus*-type are considered to be thermophilic taxa with high temperature optima in most training sets (Brooks, 2006). In a Swiss calibration dataset, *C. anthracinus* and *Dicrotendipes* are indicative of temperatures between 8 and 16°C, whereas *P. sordidellus* is characterized by a very broad temperature distribution (Heiri et al., 2011).

Plotted near the origin of PCA$_1$ axis 1, the second sub-group of samples of IGA-2 (IGA-2b) is marked by the higher relative abundance of *M. insignilobus*-type and *H. marcidus*-type and conversely slightly lower percentages of *H. subpilosus*-type. *M. insignilobus*-type and *H. marcidus*-type have higher temperature optima than *H. subpilosus*-type in northwestern Quebec (Larocque et al., 2006). *H. marcidus* is considered to be the least cold-stenothermic species of the genus (Saether, 1975). In their study of the Chironomidae in the ultraoligotrophic lake 95 (35 km west of Igaliku, Fig. 1), Lindegaard and Mæhl (1992) suggested that the in-lake distributions of *H. oliveri* (=*H. subpilosus* subfossil type) and *Heterotrissocladius changi* (=*H. marcidus* subfossil type) were explained by differences in their preference for food quality and quantity. *H. oliveri* seemed to develop better on low energy food (phytoplankton and zooplankton fecal pellets) than *H. changi*, which thrived on benthic algal production.

The third sub-group of samples (IGA-2c) is plotted at positive values along PCA$_1$ axis 1 and is characterized by high relative abundance of *H. subpilosus*-type that includes cold-stenothermic and ultraoligotrophic species.

Finally, the review of the modern ecology and distribution of the characteristic taxa for each sub-set of samples does not permit the
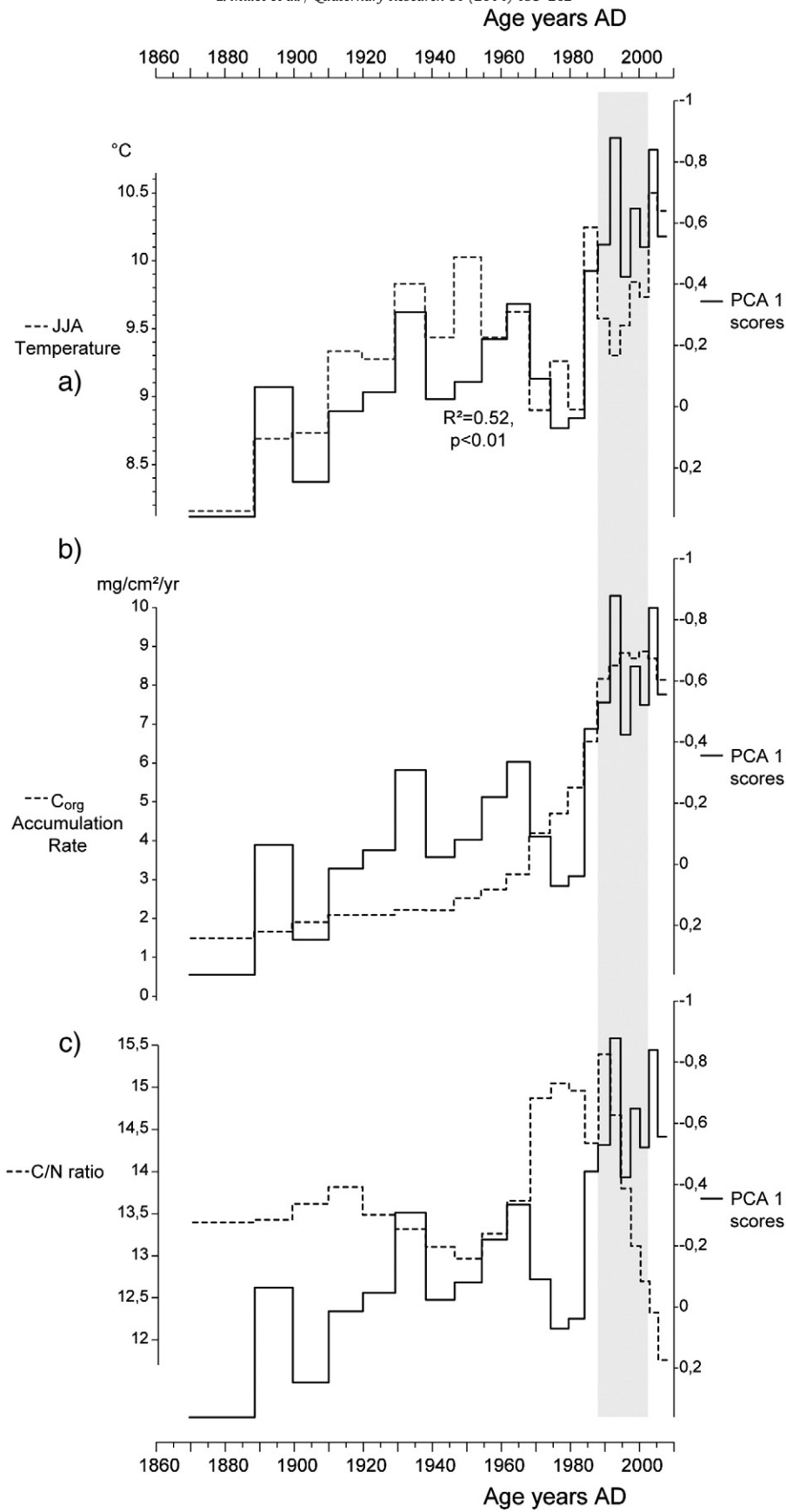
Figure 5. Relationship between sample scores along PCA$_1$ axis 1 scores and (a) mean summer temperature (JJA) recorded at the Ivittuut weather station (AD 1873–1960, gray dotted line) and at Narsarsuaq Weather station (AD 1961–2006, black dotted line); temperature records are plotted at the time resolution of the chironomid samples after the calculation of the mean value for the time period covered by each sediment sample. The R^2 and the p values of correlation are indicated; (b) organic carbon accumulation rate (C$_{org}$AR) in the sediment; and (c) the carbon nitrogen ratio in the same samples. The gray band indicated the post-1988 period when the correlation between PCA$_1$ axis 1 scores and summer temperature was lost due to anthropogenic impact on in-lake processes.

definitive identification of a main controlling factor for the major or the more subtle changes in the Lake Igaliku chironomid assemblages during the last 1500 years. The factors that possibly combined to impact the chironomid communities fell into two broad categories: climate change (air and water temperature) and in-lake processes such as trophic level or organic matter quantity and quality. In their study of lakes in Southwestern Greenland, Brodersen and Anderson (2002) already emphasized the difficulty of disentangling the respective influence of these factors which were highly correlated.

Both the major and subtle changes in the chironomid assemblages with depth (or age) can be summarized by a stratigraphic plot of PCA_1 axis 1 sample scores. A sub-set of samples and their characteristic taxa are distributed along axis 1 from the *H. subpilosus*-type dominated samples of IGA-2 at the positive end of axis 1 to samples at the negative side with lower relative abundance of *H. subpilosus*-type and conversely higher percentages of *M. insignilobus*-type or *C. arctica*-type.

Forcing factors of chironomid assemblages during the last 140 yr

To better understand the primary controlling factors for the Lake Igaliku chironomid community, i.e., climate, in-lake processes or a combination of both, we compared the PCA_1 axis 1 sample scores against age with proxies for lake functioning and available regional climate data (Fig. 5).

The last 140 yr seemed particularly suitable for testing hypotheses because (1) there is a long time series of instrumental climate data (AD 1873–2011) held at the Denmark Meteorologiske Institute for Narsarsuaq, located near Lake Igaliku (Fig. 1); (2) the temporal resolution for this time period is the highest for the Lake Igaliku sediment record (from 19 to 2 yr per sample, mean = 7 yr per sample); (3) this period is marked by high climate variability, i.e., an initial temperature increase in 1920–1950, a decrease in the 1960s and 1970s and an increase again in the 1980s (Cappelen, 2011); (4) there was a strong change in lake trophic functioning at ca. 1988 in response to a shift from Norse-analog farming to modern practices, inducing high nutrient inputs to the lake (Massa et al., 2012a; Perren et al., 2012). Summer temperature is widely acknowledged to be a key driver for chironomid distribution over large geographic scales (Brooks, 2006) through direct effects on physiology, life cycle and behavior and/or indirect influences on the physical and chemical conditions in lakes (Eggermont and Heiri, 2012). Therefore, mean summer temperatures (JJA) from Narsarsuaq were compared with changes in the chironomid assemblages as indicated by the sample score along PCA_1 axis 1 (Fig. 5). Organic matter (Corg Accumulation rate and C/N) in the sediment was used as a proxy for lake trophic functioning and was compared with the chironomid PCA_1 axis 1 scores (Fig. 5). The accumulation of OM in the sediment of the profundal zone of stratified lakes results from the supply of allochthonous material, OM production in the lake and degradation processes in the water column and in the sediment. In turn, the quantity and quality of organic matter in the sediment can influence chironomids either directly as a food source or indirectly through their impact on oxygen conditions at the sediment/water interface.

There is a significant correlation between the JJA mean temperature and the sample scores along axis 1 of the chironomid PCA_1 (Pearson correlation, $R^2 = 0.52$, $p < 0.01$, Fig. 5). In contrast, the PCA_1 axis 1 scores were not significantly correlated with $C_{org}AR$ or the C/N ratio. The concordance between chironomid assemblage changes and temperature is clear over the last 140 years, except during a short period between ca. AD 1988 and 2000 when the PCA_1 axis 1 scores do not match the relative decrease in summer temperature (Fig. 5, gray band). When the corresponding samples are removed from the dataset, the determination coefficient between the PCA_1 axis 1 scores and summer temperature is increased to 0.66 and is highly significant ($p = 4.23\,E^{-4}$). This short period is marked by the highest values of $C_{org}AR$ for the last 140 yr (and for the whole record) and by a sharp decrease in C/N ratio.

These comparisons suggest that summer temperatures were the major controlling factors for the chironomid assemblages from AD 1870 to 1988. From ca. 1920 to the mid-1980s, the Lake Igaliku catchment was used for sheep grazing (Miki Egede, personal communication). During this period, extensive sheep breeding occurred throughout the year, and very little fodder was produced. This farming practice may have had a small impact on the lake ecology (e.g., by increasing nutrient loadings) as witnessed by a slight increase in $C_{org}AR$ in the 1920s (Figs. 5 and 7). Nevertheless, these local changes seemed to have limited impacts on the chironomid assemblages, which seemed instead controlled by the changes in temperature.

The relationship between the chironomids and temperature is lost after ca. AD 1988, when $C_{org}AR$ most likely reached a threshold in impacting the chironomid fauna. This high accumulation in organic matter in the sediment coincides with changes in the local environment, i.e., the shift to modern agriculture in the Lake Igaliku watershed. With the objective of increasing fodder production and yields, massive use of fertilizers began in the mid-1980s (250–300 kg/ha per year) in the cultivated areas around the lake (Miki Egede, personal communication). The lake also suffers from effluent loadings from the nearby winter sheep stables. This led to an unprecedented increase in nutrient availability in the lake water and enhanced phytoplankton production (Massa et al., 2012a; Perren et al., 2012). Consequently, more autochthonous organic material accumulated in the sediment and most likely induced the major change in the chironomid fauna through impact on food quality and quantity.

During the period 1920–1988, when farming may be considered analogous to Norse-practices and without significant consequences on the diatom ecology (Perren et al., 2012), changes in the chironomid assemblages were primarily driven by climate. Changes in the local environment most likely remained under the threshold for the disruption of the chironomid/climate relationship. Therefore, the chironomid assemblages could be considered to be a valuable indicator of climate change (i.e., summer temperature) during the 14 preceding centuries, even if Norse settlement has slightly impacted the local environment of Lake Igaliku through moderate grazing pressure and soil erosion (Gauthier et al., 2010; Massa et al., 2012a). The predominant effect of climate on the chironomid assemblage trajectory is further supported by the lack of correlation between PCA_1 axis 1 scores and the organic matter accumulation rate ($C_{org}AR$) between AD 1920 and AD 1988 (Fig. 5).

A tentative climate record for the last 1500 yr

The high and significant correlation ($R^2 = 0.81$, $p = 0$, Pearson correlation) between axis 1 scores of PCA_1 and PCA_2 (in which samples of IGA-1 were excluded) indicated that the specific taxonomic composition of post-1988 samples did not influence the PCA_1 axis 1 scores of pre-1988 samples.

When considering the curve of the PCA_1 axis 1 scores versus age as representing temperature changes, several climatically different periods can be identified throughout the record (Fig. 6). The record begins with a phase of likely warmer climate (lower axis 1 scores) until ca. 680 AD. This is followed by a slightly milder period (higher axis 1 scores) lasting from ca. AD 680 to AD 1280 (Fig. 6). During this interval, a short-lived warm event occurred between ca. AD 1000 and 1060. The end of the 13th century is marked by a shift in climate toward colder conditions. The AD 1280–1920 time window is characterized by high climate variability. Between AD 1280 and 1460, the high values of the axis 1 scores of PCA_1 suggest a strong cooling trend (Fig. 6). Two other cold phases are suggested by high PCA_1 axis 1 scores, i.e., from AD 1640 to 1780 and from AD 1840 to 1920. These cold phases alternated with warmer periods suggested between AD 1460 and 1640 and between AD 1780 and 1840. From AD 1920 to 1988, the decrease in the PCA_2 axis 1 scores suggests a strong warming (Fig. 6). At ca. 1986, i.e. the last sample of IGA-2 covering the 1984–1988 period, the PCA_1
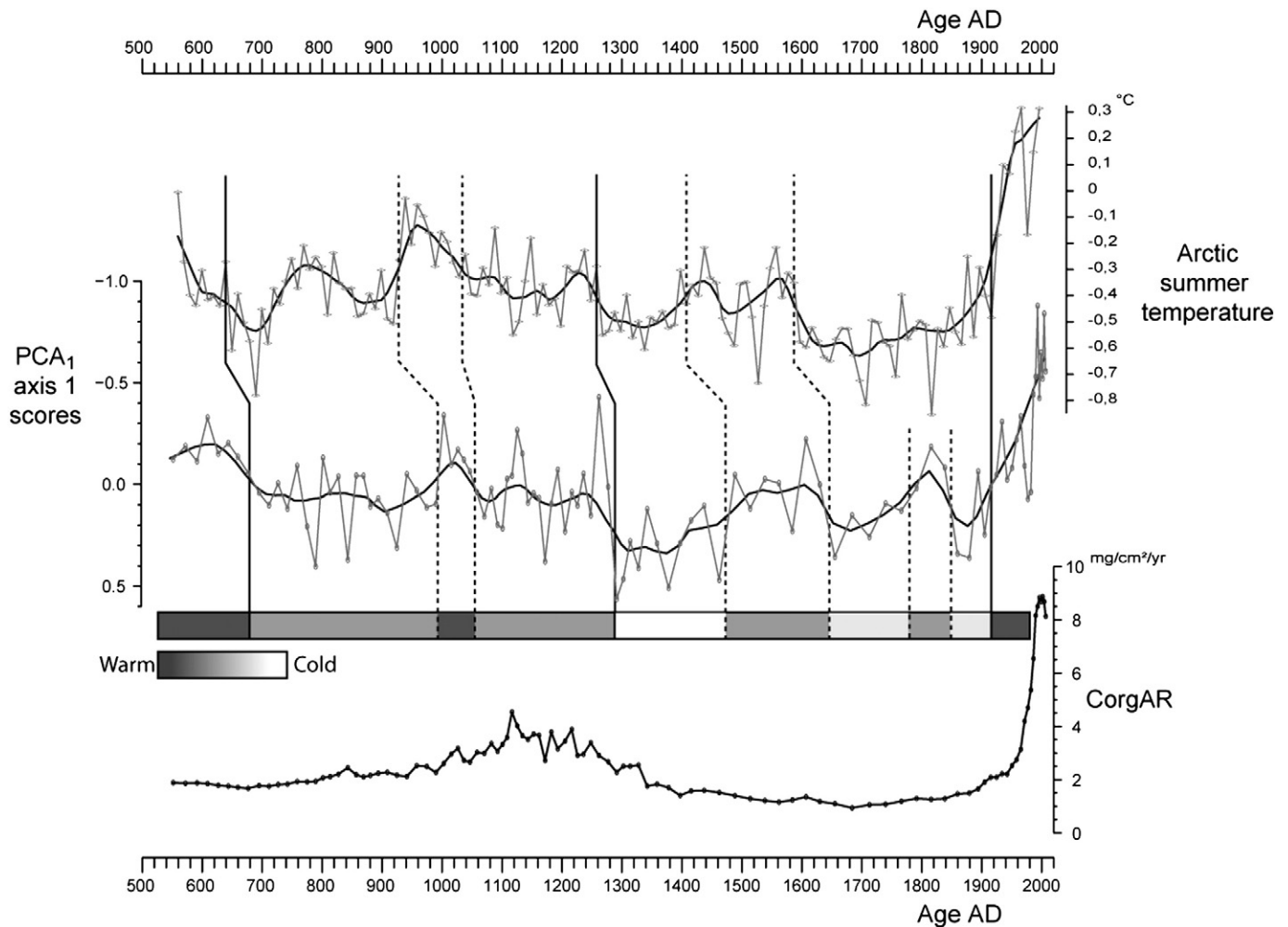
Figure 6. PCA$_1$ axis 1 scores of the Igaliku chironomid samples compared with (a) the Arctic temperature reconstruction of Kaufman et al. (2009), black line: smooth fitted curve (loess smoothing, span: 100 years) and (b) the organic carbon accumulation rate in Lake Igaliku sediment. The vertical lines indicate the main (solid lines) and minor (dashed lines) climate changes suggested by the chironomid record (PCA$_1$ axis 1 scores).

axis 1 scores are the lowest of the entire record, indicating the prevalence of unprecedented warm conditions in summer with reference to the last 1500 years. After AD 1988, the relationship between climate and chironomids is lost or strongly biased by the anthropogenic impact on the lake functioning.

These climate changes suggested by the Lake Igaliku chironomids are in overall agreement with the previous climatic reconstructions performed in the south of Greenland. Similar to the chironomids from Lake Igaliku, diatoms and foraminifera data from cores taken in the Igaliku Fjord suggested relatively warm conditions during the 885–1235 interval, which corresponds to the Medieval Warm Period (Jensen et al., 2004; Lassen et al., 2004). Warmer conditions during the MWP were also evidenced by biogenic silica and organic matter at Qipisarqo Lake (Kaplan et al., 2002), ca. 120 km west of Lake Igaliku. Reconstructions from the Igaliku Fjord indicated that the MWP was followed by a cooling that corresponded to the Little Ice Age and was marked by a more unstable climate. Foraminifera fauna suggested the culmination of a first cooling step of the Little Ice Age at ca. AD 1405 (Lassen et al., 2004). Given the uncertainties in core dating, this event may be considered as coeval to the strong cooling evidenced between AD 1280 and 1460 at Lake Igaliku. Furthermore, the warmer period indicated between AD 1460 and 1640 at Lake Igaliku clearly matches a short climatic amelioration observed within the LIA in approximately AD 1520 from the Igaliku Fjord record (Lassen et al., 2004). At Lake Igaliku, the post-LIA warming began at ca. AD 1920 as suggested by the PCA$_1$ axis 1 scores. The increase in summer temperature from AD 1920 to 1988

(the end of the relevant climate record) is in agreement with local instrumental temperature data as discussed above. This is also in accordance with the strong increase in the terrestrial pollen influx at Lake Igaliku, which suggests an increase in summer temperature after ca. AD 1920 (Massa et al., 2012b).

The results from Lake Igaliku are also in agreement with studies performed farther away in western Greenland. To the north, at Holsteinborg Dyb, marine diatom-based reconstruction indicated relatively warm conditions during the MWP (from AD 750 to 1330) followed by the LIA episode (Sha et al., 2011). At Disko Bugt (central West Greenland), Krawczyk et al. (2010) also found evidence of the MWP between AD 650 and 1250 followed by the LIA.

The pattern of climate change as depicted by the Igaliku chironomids throughout the last 1500 years is in overall agreement with the composite reconstruction of the Arctic summer temperature developed by Kaufman et al. (2009) using circumarctic climate records (Fig. 6). Some differences do exist in the timing of the main climate variations, but they never exceed the boundary of the confidence interval provided by the age–depth models (Fig. 6). There are some notable differences between the two records regarding small temporal scale and/or magnitude. The short-lived warm episode suggested by the PCA$_1$ axis 1 scores between AD 1780 and 1840 in the Igaliku record is absent from the Arctic summer temperature reconstruction (Fig. 6). Conversely, the warm interval found in the Arctic summer reconstruction at ca. AD 800 is not indicated by the chironomid record from Igaliku. These slight differences in reconstructions likely originate from the different spatial
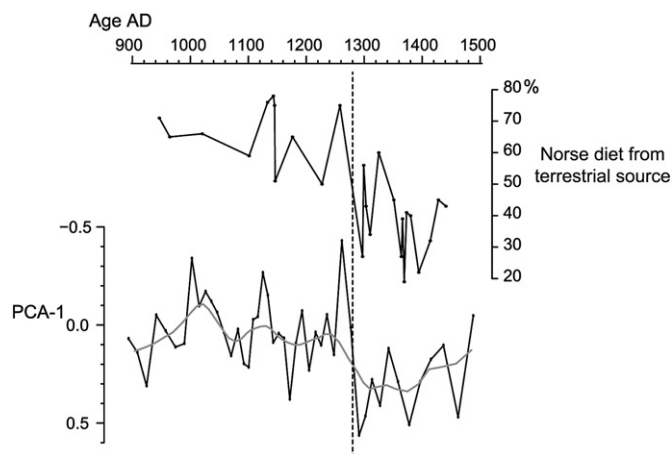
Figure 7. PCA$_1$ axis 1 scores of the Igaliku chironomid samples over the AD 900–1500 period compared with the relative proportion of terrestrial sources in the Norse diet determined from stable isotope analysis (Arneborg et al., 1999).

integration of both records. The chironomids from Lake Igaliku provide a local temperature estimate with probable specific local features, whereas the climate reconstruction of Kaufman et al. (2009) smooths the local particularities to reach a synoptic climate signal for the Arctic.

Changing climate and Norse settlement

One aspect of major interest in the climate record derived from the Igaliku chironomids is precisely to provide a local assessment of climate changes throughout the last 1500 yr within the Norse settlement area. Such a record could help to understand how climate fluctuations have driven human changes in the Eastern Settlement. The subsistence of the Norse was based on a balanced combination of pastoral farming, hunting and gathering of wild species and the exploitation of a source of trade goods (Dugmore et al., 2012). Stable carbon isotope analysis of the bone collagen in Norse skeletons (Arneborg et al., 1999) indicated that a strong change in the balance between terrestrial and marine food occurred at the end of the AD 13th century (Fig. 7). The relative proportion of marine sources in the diet of the Greenland Norse shifted from 40% before ca. AD 1300 to 80% after this turning point. Over the period AD 900–1450, there is a striking concordance between changes in the PCA$_1$ axis 1 scores and diet source (Fig. 7). The shift toward the dominance of marine sources seems strongly linked to the cooling of the local climate suggested by the chironomids at ca. AD 1280. As stated by Dugmore et al. (2012), a cold climate would have reduced livestock survival through decrease in grazing and fodder production and increased winter livestock housing time and fodder needs. Accordingly, the study of pollen and the coprophilous fungal remains as well as the soil erosion proxies from the Lake Igaliku sediment core indicated a decrease in farming activities after ca. AD 1335, perhaps beginning in AD 1230, as indicated by the organic C and N isotopic data and the complete disappearance of pastoral proxies at the beginning of the 15th century (Gauthier et al., 2010; Massa et al., 2012a). The change in diet source and more particularly the exploitation of migratory seals was considered to be a successful response of the Norse to adverse climate impacts (Arneborg et al., 1999). Although the ultimate causes of the demise of the Norse Greenland settlements are well beyond the scope of this paper, our data suggest that local climate changes may have had a significant effect on the Norse dietary economy.

Conclusion

The major shift in chironomid assemblages occurred at ca. AD 1988 (± 2 yr) and was most likely triggered by anthropogenic changes in the catchment, i.e., the conversion from traditional to modern agriculture. The unprecedented cultural eutrophication from point sources (effluent from winter sheep stables) and non-point sources (fertilizers in cultivated areas) led to enhanced phytoplankton production (Perren et al., 2012) and organic matter accumulation in the sediment that deeply impacted the benthic community, independent of climate.

The significant correlation between subtle changes in the chironomid fauna (PCA$_1$ axis 1 scores) and local instrumental temperature records ($R^2 = 0.65$ $p = 4.23$ E^{-4}) suggested that climate was the primary controlling factor for the Lake Igaliku chironomid from AD 1870 to 1988. The traditional sheep breeding occurring within the lake catchment since ca. 1920 did not disrupt the linkage between chironomid and climate.

Because the effects on the environment of Norse farming were well beyond those of the 20th century, we assessed the changes in the Lake Igaliku chironomid assemblage throughout the last 1500 yr as a climate signal. The chironomid-derived climate signal compares favorably to other climate records from western Greenland and the Arctic region. This overall agreement strongly supports the validity of the supposed chironomid-derived climate record from Lake Igaliku, which is the first continental proxy record of climate located in the Norse Eastern settlement.

Although any monocausal and environmentally deterministic explanation of the fate of the Norse Greenlanders should be avoided (Dugmore et al., 2012), the striking resemblance between the chironomid proxy temperature record of Lake Igaliku and the reconstructed Norse diet from bone isotopes (Arneborg et al., 1999) strongly support the hypothesis that climate was a key driver of the Norse subsistence, with harsher climate conditions leading to an enhanced exploitation of sea resources.

This study is an initial step in the reconstruction of climate changes over the last 1500 yr in the area of Norse settlement. Future development will involve the study of several other lacustrine records within the Western and the Eastern Settlements to assess the chironomid trajectory in a different context and to confirm if similar climate driven changes are evident. Another challenge is to develop a relevant transfer function that is able to quantitatively infer temperature changes from western Greenland chironomid records. As suggested by Brodersen and Anderson (2002), the extension of the existing western Greenland dataset is needed to increase the climatic confidence of a regional chironomid–temperature model.

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