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High resolution Lateglacial and early-Holocene summer air temperature records from Scotland inferred from chironomid assemblages

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ABSTRACT

Lateglacial and early-Holocene mean July air temperatures have been reconstructed, using a chironomid-based inference model, from lake-sediment sequences from Abernethy Forest, in the eastern Highlands of Scotland, and Loch Ashik, on the Isle of Skye in north-west Scotland. Chronology for Abernethy Forest was derived from radiocarbon dates of terrestrial plant macrofossils deposited in the lake sediments. Chronology for Loch Ashik was derived from tephra layers of known ages, the first age-depth model of this kind. Chironomid-inferred temperatures peak early in the Lateglacial Interstadial and then gradually decline by about 1 °C to the beginning of the Younger Dryas (YD). At Abernethy Forest, the Lateglacial Interstadial is punctuated by three centennial-scale cold oscillations which appear to be synchronous with the Greenland Interstadial events GI-1d, when temperatures at Abernethy fell by 5.9 °C, GI-1c, when temperatures fell by 2.3 °C, and GI-1b, when temperatures fell by 2.8 °C. At Loch Ashik only the oscillation correlated with GI-1d is clearly defined, when temperatures fell by 3.8 °C. The start of the YD is clearly marked at both sites when temperatures fell by 5.5 °C at Abernethy Forest and 2.8 °C at Loch Ashik. A warming trend is apparent during the late-YD at Abernethy Forest but at Loch Ashik late-YD temperatures became very cold, possibly influenced by its close proximity to the Skye ice-field. The rapidly rising temperatures at the YD – Holocene transition occur about 300 years earlier at both sites than changes in sediment lithology and loss-on-ignition. The temperature trends at both sites are broadly similar, although between-site differences may result from the influence of local factors. Similar climate trends are found at other sites in the northern British Isles. However, the British summer temperature records differ in detail from trends in the oxygen-isotope records from the Greenland ice-cores and from other chironomid-inferred temperature records available from Scandinavia, north-west Europe and central Europe, which suggest important differences in the influence of climatic forcing at regional scales.

1. Introduction

Climatic changes during the last glacial–interglacial transition (LGIT) between approximately 16–8 ka BP are of considerable interest to climate scientists because they provide insights into atmosphere-ocean-terrestrial climate linkages during a period of rapid, high amplitude climate change. Changes in the ratio of stable oxygen isotopes from Greenland ice-cores (e.g. Johnsen et al., 1992; Rasmussen et al., 2006; Svensson et al., 2008) provide high resolution records of temperature trends but records from elsewhere are required to determine independently the magnitude and timing of climatic trends at other locations, and to provide a framework for understanding the terrestrial environmental responses to these forcing factors. The climate of the British Isles is strongly influenced by the North Atlantic current and so is especially sensitive to changes in ocean circulation. Quantitative climate records for the LGIT from the British Isles have mostly been inferred from beetle sequences (e.g. Coope et al., 1998) but these are not as highly resolved temporally as the ice-core records, because (i) large quantities of sediment, which may have been laid down over many

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decades, are required to acquire sufficient numbers of beetle remains; (ii) the inferred temperatures are prone to large range-estimates and (iii) beetle records frequently lack precise and accurate independently derived chronologies. For these reasons most are not suitable to confirm whether or not the detailed climatic trends apparent in the ice-core record also occur in Britain. However, low error, quantitative climate records can be inferred at high temporal resolution from chironomid remains, which are preserved in large numbers as larval head capsules in lake sediments. At present, the only published Lateglacial to early-Holocene chironomid-inferred temperature records from Britain and Ireland are from Whitrig Bog, south-east Scotland (Brooks and Birks, 2001), Lough Nadourcan, western Ireland (Watson et al., 2010), Fiddaun in western Ireland (van Asch et al., 2012), and five sites in the English Lake District (Bedford et al., 2004; Lang et al., 2010). These records show general similarities between each other and with the ice-core records but there are differences in detail, which may reflect regional climatic differences or may be related to the low precision of the chronological data available to anchor and correlate each record temporally. In addition, lake size, depth and morphometry may influence the chironomid-based temperature reconstructions (Lang et al., 2010). Thus, more high resolution records with well-founded, independently derived, chronologies are required to quantify the magnitude, timing and rate of climate change in the British Isles during LGIT and establish the extent of regional and local differences in these trends and in other records across Europe.

We use chronology and temperature trends derived from our sites to compare with the Greenland ice-core eventstratigraphy proposed by Lowe et al. (2008). Radiocarbon chronologies frequently have large uncertainties which make correlation difficult with the climatostratigraphic units defined for Scandinavia (Mangerud et al., 1974) and for Greenland (Rasmussen et al., 2006). Here, for convenience, we adopt a simplified LGIT climatostratigraphic terminology of Lateglacial Interstadial-Younger Dryas-Holocene as these are widely used terms in the literature relating to well-defined climatic events. This scheme is only used for the broad sub-divisions of stratigraphical units and not to infer any precise chronological associations to each unit. Ultimately, comparisons are made to the Greenland event-stratigraphy outlined in Lowe et al. (2008).

There have been many investigations into vegetational change in response to climate change in the Lateglacial and early-Holocene in Britain, and regional trends are now well-established (Walker et al., 1994). Certain localities having detailed pollen sequences have been nominated as reference sites (Walker, 1993). They include Abernethy Forest near the Cairngorm mountains in north-east Scotland (Birks and Mathewes, 1978), and Loch Ashik on the Isle of Skye in north-west Scotland (Walker and Lowe, 1990, 1991). These records provide evidence of rapid vegetational changes to climate warming at the beginning of the Lateglacial Interstadial (equivalent to the Bølling-Allerød interstadial in mainland Europe and GI-1 in Greenland), to cooling during the Younger Dryas (GS-1), and finally to rapid warming at the start of the Holocene. Less severe cooling events during the Lateglacial Interstadial may also be suggested by vegetation responses. However, these important pollen sequences cannot be placed in an independently derived climatic context until quantitative, high resolution climate reconstructions with well-founded and precise chronologies are available.

This is the focus of the present study. We provide high temporal resolution chironomid-inferred mean July air temperature records for Loch Ashik and Abernethy Forest and compare them against other high resolution temperature records from Britain, mainland north-west Europe and Greenland to determine regional and local trends. We briefly compare the chironomid-inferred estimates with summer temperature estimates derived from beetles and also with changes in pollen assemblages. The addition of these detailed chironomid sequences and their accompanying mean July air temperature estimates to the pollen records from these two Scottish sites considerably enhances their value as reference sites for the LGIT.

2. Study sites

Loch Ashik (57°14′32.73″N; 05°49′39.89″W) (Fig. 1) is located in the south-east of the Isle of Skye, western Scotland, about 5 km east of Broadford. Mean July air temperature at Kinlochewe (57°36′016.2″N, 5°19′59″W; 145 m asl) is 14.4 °C (Meteorological Office data for 1971–2000 [www.metoffice.gov.uk]). The loch lies on Torridonian sandstone, which is slightly calcareous in parts. The lake is about 150 m long by about 130 m wide and is situated at about 50 m asl. Streams enter at both the western and eastern ends and there is an out-flowing stream at the north end. Our core was taken from below soft peaty ground at the in-filled western end of the loch near the water's edge, close to the site from where Walker and Lowe (1990) described a LGIT pollen sequence and from where the Vedde Ash was described by Davies et al. (2004). Lake sediments corresponding to the LGIT were situated below peat at a core depth of 500–675 cm (Table 1).

Abernethy Forest (57°14′13.08″N; 03°42′25.65″W) (Fig. 1) is in the Cairngorms region of north-east Scotland, about 10 km north-west of Aviemore. Mean July air temperature at Braemar (57°00′20.88″N, 3°23′53″W; 340 m asl) is 13.4 °C (Meteorological Office data for 1971–2000 [www.metoffice.gov.uk]). The coring site is in the in-filled south-western end of Loch Garten (about 1100 m long by about 670 m wide, altitude about 230 m asl) and is situated to the south of a channel linking the loch with Loch Mallachie. The base of the Lateglacial lake-sediment was situated at a core depth of about 700 cm. Our coring site is close to the sites used by Birks (1970) and Birks and Mathewes (1978) to describe LGIT pollen and plant macrofossil sequences.

3. Material and methods

3.1. Coring

Six overlapping core sequences, less than 1 m apart, were taken at Loch Ashik using a 7.5-cm diameter square-rod Livingstone piston corer (Wright, 1967). The early-Holocene and Lateglacial sequence was covered in two drives in each core. The longest sequence (series VI) was 172 cm. The cores were correlated by lithological changes and loss-on-ignition analysis (LOI).

Three overlapping core sequences were taken from Abernethy Forest using the same corer. The LGIT sediments were recovered in three drives in each sequence. The longest sequence (285 cm) was obtained from core series III but core series II was used to provide overlap at the core junction between the second and third drives of series III (at 600 cm). The cores were correlated by sand layers and LOI analysis.

All the cores were sliced at 1 cm intervals. The cores were stored at 4 °C and Abernethy Forest macrofossil samples were stored at −20 °C.

3.2. Chronology

Fourteen radiocarbon AMS dates were obtained from Abernethy Forest based on terrestrial plant macrofossils. An age-depth model was constructed using a Bayesian-based *P_Sequence* within the OxCal v4.1 program in combination with the IntCal09 calibration set (Reimer et al., 2009). The *P_Sequence* is a Poisson–process

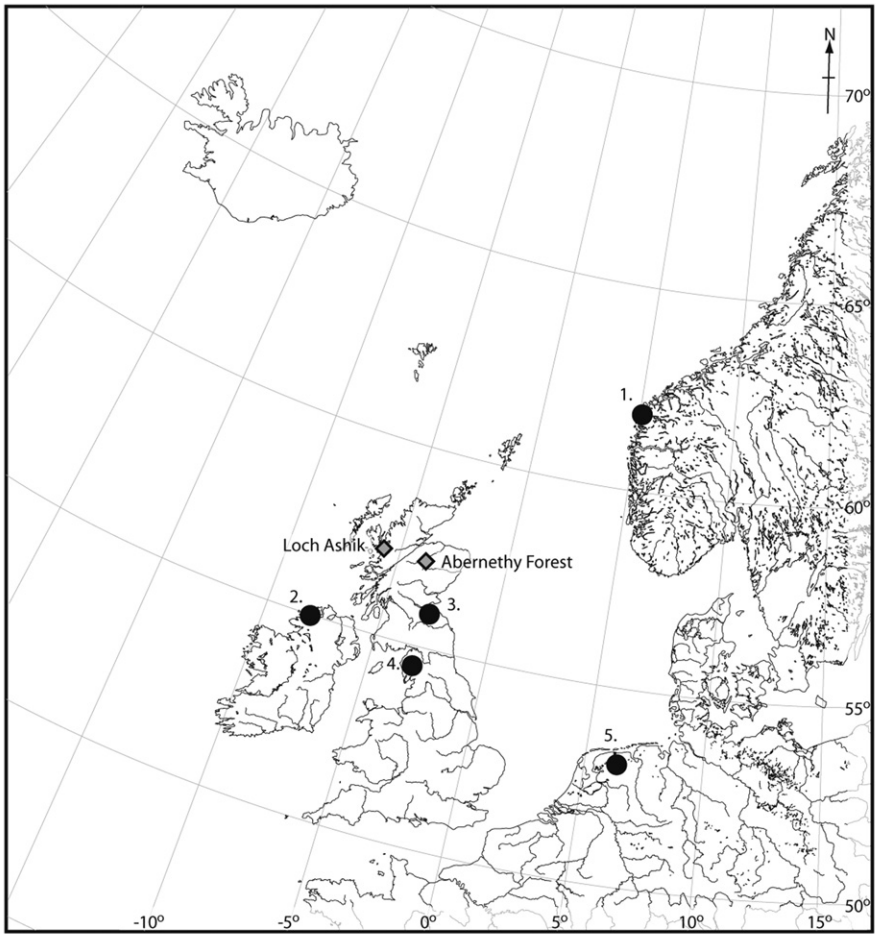

Fig. 1. Location of Loch Ashik and Abernethy Forest and other sites referred to in the text (1: Kråkenes; 2: Lough Nadourcan; 3: Whitrig Bog; 4: Hawes Water; 5: Hijkermeer).

depositional model which allows for changing depositional rates within a sediment sequence. This flexibility is achieved through altering the rigidity of the model via parameter '*k*'. High '*k*' values assume close to linear sedimentation while lower values allow greater flexibility. Additionally, these models permit the inclusion of depth and stratigraphical information within the model. The calculated likelihood of the models was checked via the OxCal agreement index using a value of 60% as a lower cut off (for a full explanation of the OxCal terminology and modelling procedures see Bronk Ramsey, 2008, 2009). More details of the final age model, which was used to make best-estimates of the ages of the tephras in the sediments, are presented in Matthews et al. (2011).

Table 1
Lithostratigraphical description of the sediment sequence recovered from Loch Ashik.

Depth (cm from mire surface)	Composition
500–569	Dark brown gyttja with coarse detritus at top getting gradually finer
569	Sharp sloping boundary to clay
569–578	Variable pinkish brown or pale grey clay with dark flecks
578.0–578.5	Black Vedde Ash
578.5–587	Variable pinkish brown or pale grey clay with dark flecks
587	Sharp boundary between clay above and gyttja below
587–600	Olive-brown firm fine-detritus gyttja with scattered dark flecks of moss, about 25% silt
600–625	Olive-brown firm fine-detritus gyttja with scattered dark flecks of moss, about 50% silt
625–635	Grey firm silty gyttja with moss inclusions
635–637	Mid-brown silty gyttja, moss absent
637–648.5	Yellow-brown firm silty gyttja, becoming greyer with depth. Moss infrequent
648.5–651.5	Pinkish firm clay-gyttja. Few moss flecks
651.5–672	Finely laminated brownish grey hard clay-silt with pink and black layers. Layers more distinct below pink band at 665 cm.

Too few plant macrofossils were found in the Loch Ashik sequence for radiocarbon dating. Bulk sediments are not suitable for dating because of the old carbon reservoir effect caused by carbonate in the sediments derived from the bedrock. These problems are common when attempting to derive chronologies for Lateglacial sequences in Britain. Therefore, the age-depth model for Loch Ashik is based solely on tephrochronology using the age-estimates derived from the Abernethy Forest age-depth model for the Borrobol and Penifiler tephras (Matthews et al., 2011).

For the tephrostratigraphical analysis, 0.5 cm^3 volumes from each 1 cm sample were sieved between 80 and 25 μm meshes to remove coarse sand particles (>80 μm) and obscuring silts and clays (<25 μm). The samples were then processed following Blockley et al. (2005). Shards were picked from samples containing shard maxima, mounted on resin stubs and polished for geochemical analysis by WDS–EPMA (Wavelength-Dispersive X-Ray Spectroscopy–Electron Probe Micro-Analyser). Tephra layers were detected in the same stratigraphical positions as those previously reported for Loch Ashik (Pyne-O'Donnell, 2011).

Correlations between these layers and previously recognised ashes across Scotland were made by geochemical comparisons to published datasets (Pyne-O'Donnell, 2007). The tephra investigations at Abernethy are reported by Matthews et al. (2011) and the Loch Ashik tephra investigations are reported in Pyne-O'Donnell (2011). Besides providing a chronological framework for the Loch Ashik sequence, we use tephra layers here to provide stratigraphical and chronological links between the Loch Ashik and Abernethy Forest chironomid data and to allow direct comparison between Loch Ashik, Abernethy Forest and other regional climate archives where these tephras have been identified.

3.3. Loss-on-ignition analysis (LOI)

Following Heiri et al. (2001), LOI analysis was carried out on contiguous samples at 1 cm intervals on cores II (overlap) and III from Abernethy Forest and on core VI from Loch Ashik, which are the same cores used for chironomid analysis. LOI at 550 °C as a percentage of dry weight was used as a proxy for organic content of the sediments.

3.4. Chironomid analysis

Altogether 83 samples were analysed from Loch Ashik, between core depths 500 and 652 cm, and 126 samples from Abernethy Forest, between core depths 410 and 691 cm. At both sites the cores were analysed initially at 4 cm intervals but then resolution was increased to 2 cm or 1 cm intervals at points in the sequence which showed critical changes in the chironomid assemblages or in the inferred temperatures.

Sample preparation for chironomid analysis followed Brooks et al. (2007) using warm 10% KOH and Euparal slide mountant. The head capsules were identified using a compound microscope at 100–400× magnification, with reference to Cranston (1982), Wiederholm (1983), Rieradevall and Brooks (2001), Brooks et al. (2007) and the chironomid collection housed at the Natural History Museum, London.

3.5. Data analysis

The chironomid results are presented stratigraphically using TGVIEW v. 2.0.2 (Grimm, 2004). The stratigraphies were zoned by optimal partitioning using the program ZONE v. 1.2 (Juggins, 1991) and statistically significant zones were identified by comparison with a broken stick model (Bennett, 1996) using the program BSTICK v. 1 (JM Line and HJB Birks, unpublished). CANOCO v. 4.5 (ter Braak and Šmilauer, 2002) was used for multivariate analyses. In all these analyses percentage abundance data were square-root transformed to stabilise variances and rare taxa were down-weighted. Detrended canonical correspondence analysis (DCCA), with detrending by segments, non-linear rescaling, and constrained by sample order was used to determine the amount of compositional turnover (Birks and Birks, 2008). Use of DCCA is essential as taxon turnover estimates based on detrended correspondence analysis (DCA) are not constrained to the stratigraphical sequence (Birks, 2007). Canonical correspondence analysis (CCA) was used to assess the environmental variables that may have influenced the response of the fossil chironomid assemblages (Birks et al., 1990; Velle et al., 2005). The fossil samples were plotted passively in CCA ordination space of a modern Norwegian calibration dataset (Brooks and Birks, 2000a; 2001, 2004; unpublished) which included the four environmental variables that had a statistically significant influence on the distribution and abundance of the modern chironomid taxa. These are mean July air temperature (which explains 48% of the total variance explained by the subset of four environmental variables), depth (14.0%), conductivity (7.6%) and alkalinity (7.6%). The CCA used Hill's scaling and inter-sample distances to provide estimates of the turnover distances of the samples (Birks et al., 1990).

3.6. Temperature reconstruction

Mean July air temperature estimates were derived from the square-root transformed fossil chironomid percentage abundance data using a modern Norwegian chironomid-based temperature calibration dataset expanded from the previously published 109-lake calibration set (Brooks and Birks, 2001). It consists of 157 Norwegian lakes spanning mean July air temperatures of 3.5–16 °C, latitudes from 80°N to 58°N, altitudes from 0 to 1600 m, and 142 chironomid taxa. After removing four outlier lakes from the dataset to improve the fit of the temperature model, the minimal adequate model with the best predictive power is a 2-component weighted-averaging partial least squares (WA-PLS) inverse regression model that has a root mean squared error of prediction (RMSEP) of 1.06 °C, a coefficient of determination (r^2_{jack}) of 0.91, and a maximum $bias_{jack}$ of 1.05 °C, all estimated by leave-one-out cross-validation. Sample specific errors of the inferred temperatures were estimated by 1000 bootstrap cycles using WA-PLS (Juggins and ter Braak, 2001). The Norwegian and North British chironomid faunas are similar, so modern Norwegian data can be used to reconstruct temperatures in the British Isles, especially as temperatures were colder in the LGIT than today.

Goodness-of-fit to temperature was evaluated by passively positioning the fossil samples on a CCA of the modern training set constrained solely against July temperature. Any fossil samples that had a squared residual distance value within the most extreme 10% of values in the modern training set were considered to have a poor fit-to-temperature. The modern analogue technique (MAT) was used to detect fossil samples that lacked good analogues in the modern calibration dataset using squared chord distance as a measure of dissimilarity. Samples with a dissimilarity larger than the 95% threshold in the modern data were considered as having no good analogues in the modern calibration dataset (Birks et al., 1990; Birks, 1995, 1998; Velle et al., 2005). The taxon percentage abundance data were untransformed prior to this analysis.

4. Results

4.1. Chronology

4.1.1. Abernethy Forest

The age-depth model was based on 12 radiocarbon dates, after two dates were rejected (Fig. 2a) (Matthews et al., 2011). This model is generally well-constrained through the first part of the Lateglacial Interstadial where the uncertainties are comparable or better than the counting errors produced for NGRIP (Lowe et al., 2008). The uncertainties increase higher in the sequence. During the YD the uncertainties are as high as +/− 500 years for some samples, as a consequence of the scarcity of dateable material coupled with a varying deposition rate.

4.1.2. Loch Ashik

No radiocarbon dates were obtained here, so an age-depth model was developed using the five ash layers (Fig. 2b) detected through the sequence. This is the first published age-depth model for the Lateglacial period in Northern Europe derived entirely from tephra dating. The Borrobol and Penefiler tephras were detected in Lateglacial Interstadial sediments at 652 cm and 610 cm, respectively, while the Vedde Ash was recognised as a visible tephra layer at 577 cm. In the early-Holocene sediments, tephra layers were

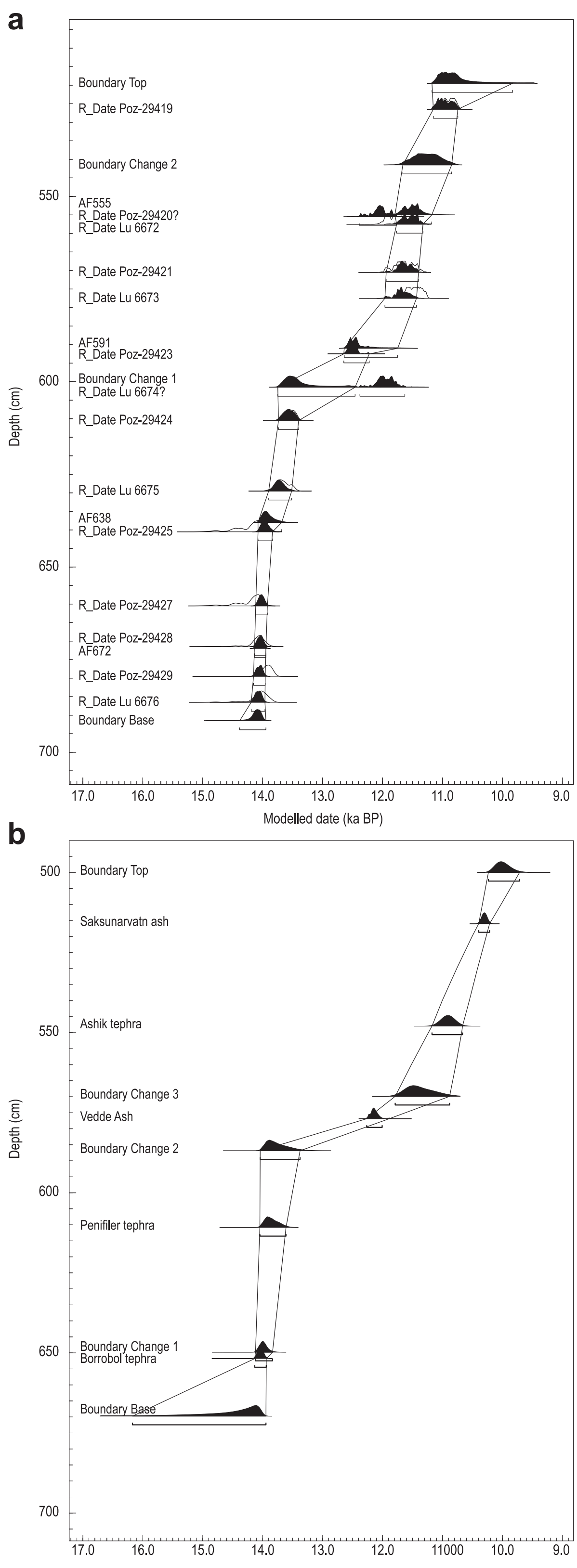

Fig. 2. The *P_Sequence* age models used in this study: (a) Abernethy Forest; (b) Loch Ashik. The models were generated using OxCal v. 4.1 (Bronk Ramsey, 2009) and the IntCal09 calibration set (Reimer et al., 2009) (full details are reported in main text). The model displays highest probability density functions for the radiocarbon dates, major lithostratigraphic boundaries, and tephra age-estimates. Boundaries were placed where the major shifts in lithostratigraphy were identified (Bronk Ramsey, 2008). Both models have relatively small uncertainties within the early Lateglacial interstadial period. These chronological uncertainties are larger in the latter part of the Lateglacial interstadial and Younger Dryas, and remain so at Abernethy Forest during the early-Holocene. However, the presence of the Saksunarvatn ash at Loch Ashik means that the age model is better constrained during the early-Holocene.

detected at 548 cm and 515 cm and these were correlated with the Ashik and Saksunarvatn tephras. The ages of the Borrobol (14140–13950 cal yr BP) and Penifiler (14090–13650 cal yr BP) tephras were based on the estimated ages for these layers at Abernethy Forest (Matthews et al., 2011). The ages used for the Vedde Ash (12171 ± 114 GICC05 yr BP) and Saksunarvatn Ash (10347 ± 89 GICC05 yr BP), are those from the NGRIP ice-core (Rasmussen et al., 2007). The age range used for the Ashik tephra is relatively broad as no precise age estimate is currently available for this tephra. Its stratigraphical position, just above a change in sediment composition that has been correlated with the Pre-boreal Oscillation, suggests it post-dates this event and thus a relatively broad age of 11200–10700 calendar years BP was used here (Pyne-O'Donnell, 2007). This age determination could be significantly improved through radiometric dates on organic sediments associated with this layer elsewhere in Scotland. The ages of the tephra layers were used to construct an age model using the same approach as at Abernethy Forest. The *P_Sequence* age model includes a *k*-factor of 2 and produces an overall agreement index of 81.1%. The model produces generally well-constrained estimates through the first part of the Lateglacial Interstadial where the uncertainties are similar to Abernethy Forest and the total NGRIP counting errors (Lowe et al., 2008). The model is least well-constrained through the later parts of the Lateglacial Interstadial and in the YD, mostly due to the lack of dates.

4.2. *LOI and lithology*

The detailed sediment lithologies are shown in Tables 1and 2 and summarised graphically in Figs. 3 and 4. LOI values are generally lower at Loch Ashik than Abernethy Forest (Figs. 7 and 8). In both sequences LOI is around 1% during the deglacial period, gradually rises throughout the Lateglacial Interstadial, and peaks at the end of the Lateglacial Interstadial at about 15% at Loch Ashik and 25% at Abernethy Forest. At both sites LOI abruptly falls at the beginning of the Younger Dryas (YD) and falls to below 5% at Loch Ashik in the late-YD or remains at between 5 and 10% throughout the YD and into the earliest Holocene at Abernethy Forest. In the early-Holocene there is a rapid rise in LOI to 25% at Loch Ashik and 35% at Abernethy Forest, and then more gradual rises, reaching 40% at Loch Ashik and 60% at Abernethy Forest by the top of each sequence.

4.3. *Chironomid assemblages*

4.3.1. *Loch Ashik*

Altogether 83 chironomid taxa were identified to genus or species-morphotype. Seven significant assemblage zones were identified (Fig. 3).

The early Lateglacial Interstadial (zone Ash-Ch1) is dominated by cool-temperate taxa, in particular *Microtendipes pedellus*-type, which suggests that relatively warm, mesotrophic conditions prevailed even in the earliest samples. The presence of *Dicrotendipes nervosus*-type suggests there may have been aquatic macrophytes in the lake (Moller Pillot and Buskens, 1990; Brodersen et al., 2001). The appearance of several cold stenothermic taxa and the ultra-cold stenotherm *Micropsectra radialis*-type at around 13940 ± 250 cal yr BP (635 cm) (zone Ash-Ch2) suggests a response

Table 2
Lithostratigraphical description of the sediment sequence recovered from Abernethy Forest.

Depth (cm from mire surface)	Composition
500–541	Coarse detritus gyttja with monocoyledonous rhizomes
541–543	Transition between silty and sandy gyttja and coarse detritus gyttja
543–544	Coarse silty and sandy gyttja
544–544.5	Sand layer
544–549	Coarse silty-sandy gyttja
549–549.5	Sand layer
549.5–570.5	Firm silty gyttja with thin fine-sand layers at 555, 556,558, 567, 568, 570.5 cm
570.5–600	Firm silty gyttja with indistinct darker bands of plant material. Lower boundary distinct
600–601	Pale silty band
601–608	Dark brown firm gyttja with silt
608–615	Medium brown firm gyttja
615–617.5	Dark brown gyttja
617.5–619.5	Paler gyttja
619.5–621	Dark brown gyttja
621–623	Firm brown gyttja with plant remains
623–623.5	Thin (0.5 cm) sand layer
623–632.5	Dark brown firm silty gyttja with plant remains
632.5–646	Medium brown firm silty gyttja
646–652.5	Dark brown silt gyttja
652.5–675	Complex of thin grey and cream silt, grey sand, brown gyttja layers
675–691	Grey silt

to climate climatic cooling at this time and the fall in head capsule concentrations suggests falling lake productivity, as chironomid biomass is linked with food availability (e.g. Tokeshi, 1986). This cold oscillation lasted about 90 years. By 13850 ± 380 cal yr BP (616 cm) the assemblage had become more diverse and included a wide range of cold and temperate taxa (zone Ash-Ch3). The high abundance of *Corynocera ambigua* suggests there may have been charophytes growing in the lake (Brodersen and Lindegaard, 1999).

In the early-YD (zone Ash-Ch4) there are large increases in ultra-cold stenotherms and declines in several temperate taxa, together with a fall in head capsule concentration, indicating rapidly cooling temperatures and decreasing lake productivity. The appearance of *Pseudosmittia*, which is typically found in terrestrial or semi-terrestrial habitats or in the splash-zone of lakes (Strenzke, 1950; Cranston, 1982), may be in response to a lowering of lake level and suggests a period of greater aridity. In the late-YD (zone Ash-Ch5) the assemblage is dominated by a few ultra-cold stenotherms and the head capsule concentration falls to its lowest in the entire sequence, suggesting extremely cold temperatures and low lake productivity.

In the earliest Holocene (zone Ash-Ch6 from 11400 ± 773 cal yr BP, 571 cm) rapidly rising temperature is suggested by a sudden change in the assemblage, which becomes more diverse and is dominated by cool-temperate taxa plus a few thermophilic taxa. The abundance of *D. nervosus*-type and *Polypedilum nubeculosum*-type suggests aquatic macrophytes may have been present. Further declines in cold stenothermic and cool-temperate taxa, and the rise in temperate and thermophilic taxa after 10800 ± 475 cal yr BP (543 cm) (zone Ash-Ch7), suggests further gradual climate warming in the early-Holocene.

4.3.2. Abernethy Forest

Altogether 76 chironomid taxa were identified to genus or species-morphotype. Nine significant assemblage zones were identified (Fig. 4).

The early Lateglacial Interstadial (zone Aber-Ch1) is dominated by temperate and cool-temperate taxa. At about 13980 ± 120 cal yr BP (647.5 cm) several cold and ultra-cold stenotherms appear in the assemblage indicating a cold period (zone Aber-Ch2; GI-1d), which lasts until about 13870 ± 170 cal yr BP (635 cm) (110 years). Subsequently, a diverse assemblage of cool-temperate and temperate taxa dominate for the rest of the Lateglacial Interstadial (zones Aber-Ch3 and Aber-Ch4). The peak in the abundance of the cold stenotherm *Sergentia coracina*-type and the decline in the cool-temperate taxon *Tanytarsus glabrescens*-type at about 13550 cal yr BP ±200 (609 cm) may reflect a short period of cooler summers.

A response to rapid cooling at the start of the YD is evident at about 13000 ± 610 cal yr BP (600 cm) when ultra-cold and cold stenotherms dominate the assemblage (zone Aber-Ch5). In the late-YD, from about 11700 ± 270 cal yr BP (575 cm), rising temperatures are indicated by the increasing diversity of cold stenotherms (zone Aber-Ch6). Further warming during the YD – Holocene transition, after about 11550 ± 225 cal yr BP (557.5 cm), is indicated by declines in cold stenotherms and an increase in cool-temperate and temperate taxa (zone Aber-Ch7). The presence of *D. nervosus*-type and *P. nubeculosum*-type suggests that aquatic macrophytes were present in the lake. Plant macrofossil and pollen analyses (Birks and Mathewes, 1978) show that *Nitella* was abundant, *Ranunculus trichophyllus*-type was rare, and *Myriophyllum alterniflorum* and *Chara* were extremely rare at this time. These taxa, plus *Potamogeton filiformis*, were also present in the Allerød, so they did not become established in the YD. Although *D. nervosus*-type was present during the Allerød, *P. nubeculosum*-type was absent.

The complete replacement of cold stenothermic taxa by cool-temperate and temperate taxa, together with the sharp rise in the thermophilic taxon *P. nubeculosum*-type, occurs in the early-Holocene at about 11250 ± 400 cal yr BP (541 cm) (zone Aber-Ch8). Continuing rising temperatures in the early-Holocene are indicated by the appearance of several thermophilic taxa above core depth 493 cm, in particular *Pseudochironomus prasinus*.

4.4. Gradient analysis of fossil chironomid assemblages

At Loch Ashik the trajectory in the fossil sample scores is primarily along CCA axis 1 (Fig. 5) indicating the fossil assemblage was mostly responding to temperature change. However, during the late-YD, in particular, but also in the early-YD, there are shifts along CCA axis 2. Lake depth, conductivity and alkalinity are the major gradients on axis 2, together explaining 28% of the variation in the modern species data ($p = 0.002$). This suggests that changes in the composition of the chironomid fauna during the later part of the YD may in part be driven by an increase in lake depth or decreases in conductivity and alkalinity. DCCA (Fig. 7) shows the highest compositional turnover occurred in the GI-1d cold oscillation (635–619 cm: 0.89 standard deviation (SD) units) and during the earliest Holocene (571–541 cm: 1.02 SD units). The total taxon turnover through the whole sequence is 1.99 SD units.

The trajectory of assemblage change at Abernethy Forest is mostly along the CCA axis 1 temperature gradient but there are also some shifts along CCA axis 2 during the late-YD (Fig. 6). The overall compositional turnover (2.18 SD units) is greater than at Loch Ashik. The periods of highest assemblage turnover occurred in the GI-1d cold oscillation from 648 to 635 cm (1.15 SD units), during the transition between the Lateglacial Interstadial and start of the YD (601–595 cm: 1.35 SD units), and during the period of rising temperatures during the YD – Holocene transition (559–540 cm: 1.58 SD units) (Fig. 8).

4.5. Temperature reconstructions

The LGIT chironomid-inferred mean July air temperature (C-IT) reconstructions for Loch Ashik and Abernethy Forest are shown in Figs. 7 and 8, respectively, and are compared with the NGRIP record in Fig. 9. At both sites, C-IT is around 12 °C at the base of the

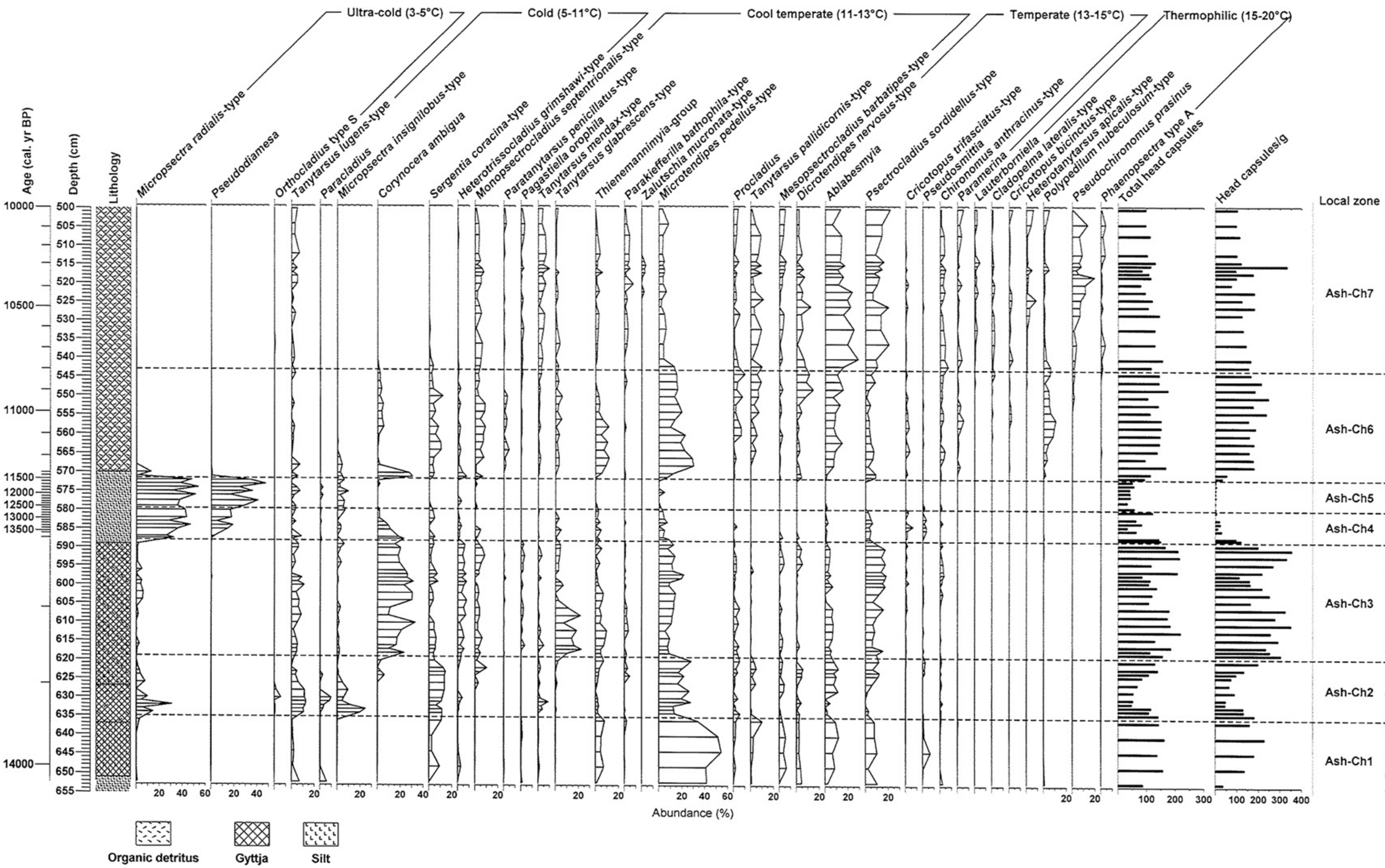

Fig. 3. Relative abundances (percentages of the total) of the dominant chironomid taxa present during the Lateglacial and early-Holocene at Loch Ashik. Taxa are plotted left to right in order of their temperature optima in the modern Norwegian calibration set, coldest at left. The range of temperature optima that characterise each taxon group is shown.

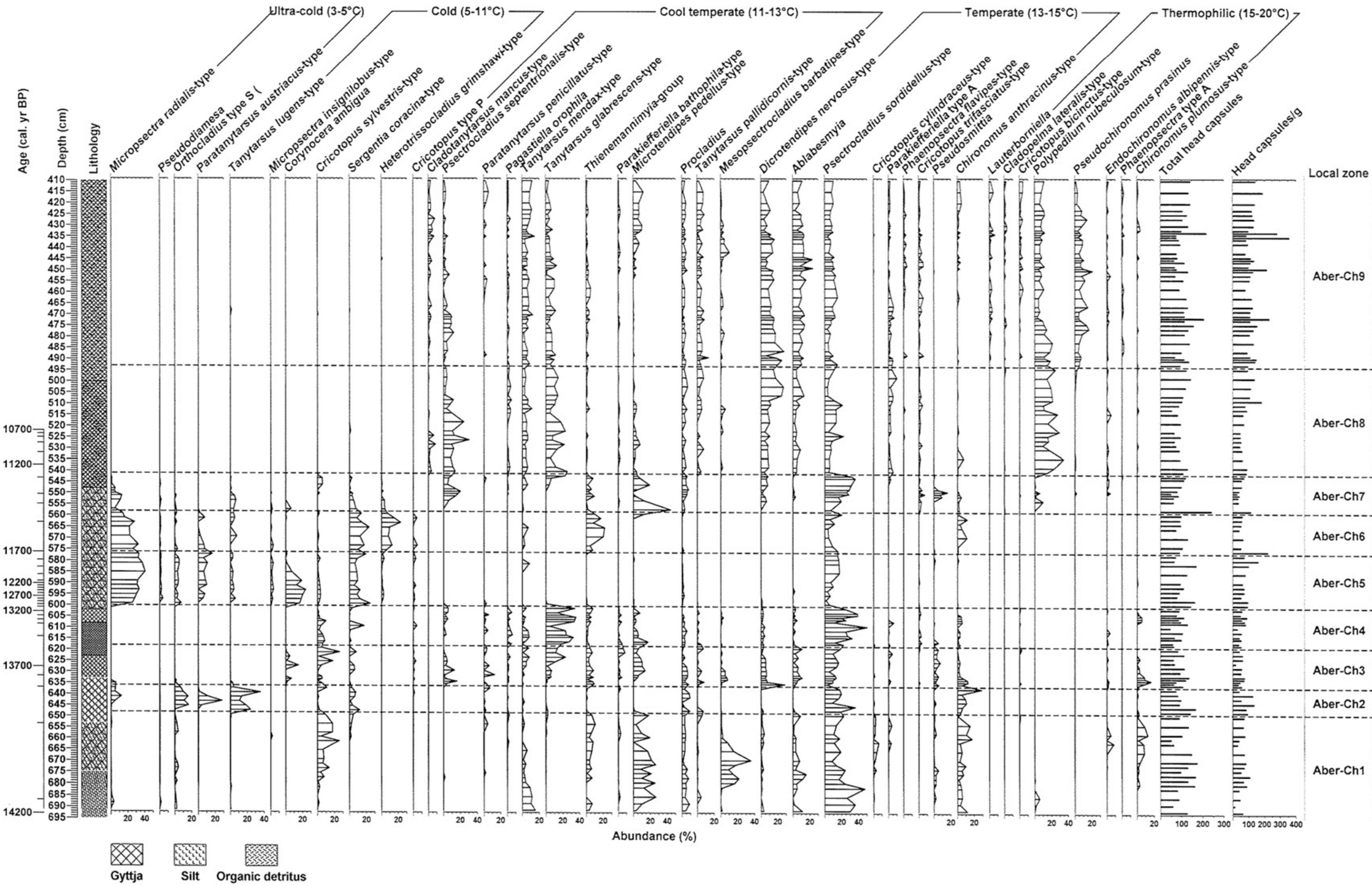

Fig. 4. Relative abundances (percentages of the total) of the dominant chironomid taxa present during the Lateglacial and early-Holocene at Abernethy Forest. Taxa are plotted left to right in order of their temperature optima in the modern Norwegian calibration set, coldest at left. The range of temperature optima that characterise each taxon group is shown.

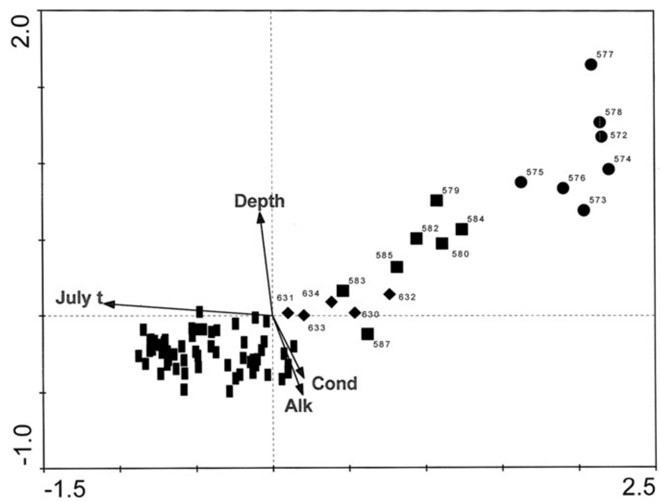

Fig. 5. Fossil samples from Loch Ashik plotted passively in canonical correspondence analysis (CCA) space of the modern Norwegian calibration dataset. The four significant environmental variables explaining variance in the modern samples are shown as biplot arrows: July *T* (mean July air temperature), Depth (maximum lake water depth), Alk (alkalinity), Cond (conductivity). The number next to each plot denotes the sample depth (cm); diamonds represent samples during GI-1d, squares represent samples during early-YD, circles represent samples during late-YD, rectangles represent all other samples.

sequence, which is higher than expected and suggests that the basal sediments from the deglacial period were not found, or perhaps that the lakes were not open for colonisation before the rise in temperatures. In other published British and Irish records (Brooks and Birks, 2001; Lang et al., 2010; Watson et al., 2010; van Asch et al., 2012), temperatures similar to the YD have been inferred from chironomid assemblages early in the deglaciation phase. At both sites, early Lateglacial Interstadial C-IT increase to reach maxima of about 13.6 °C at Abernethy Forest and 12.5 °C at Loch Ashik. Both records then indicate a substantial cold oscillation as C-IT declines by 4.4 °C at Loch Ashik and 5.6 °C at Abernethy Forest. The age-depth model for Abernethy Forest gives a date of 13960 ± 120 cal yr BP (641 cm) for the coldest point in this oscillation, while at Loch Ashik this point occurs at 13930 ± 130 cal yr BP (633 cm). The ranges of both of these estimates fall within the range of the date of 14080 ± 169 GICC05 yr BP given for the GI-1d oscillation in the GRIP and NGRIP records (Björck et al., 1998; Lowe et al., 2008). This oscillation has been correlated with the Aegelsee Oscillation (Lotter et al., 1992), which has a reported age in the Hijkermeer (Netherlands) C-IT record of 14100–14000 cal yr BP (Heiri et al., 2007). After this cold oscillation, C-IT rises again to 13.2 °C at Abernethy Forest and to 11.9 °C at Loch Ashik.

The NGRIP record shows a cold oscillation of intermediate amplitude at 13640 ± 160 GICC05 yr BP within the phase that has been referred to as GI-1c. This oscillation may be reflected in the Abernethy Forest record by a cold oscillation of about 1.9 °C dated to 13680 ± 190 cal yr BP (626 cm). The NGRIP record indicates a final Lateglacial Interstadial cold oscillation, GI-1b, which reaches minimum temperatures at 13160 ± 150 GICC05 yr BP. However, the age model for Abernethy Forest is less well-constrained towards the end of the Lateglacial Interstadial, and a final Lateglacial Interstadial cold oscillation of about 2.6 °C, which is stratigraphically in the position of GI-1b, has a date of 13520 ± 220 cal yr BP (610 cm). At Loch Ashik a cold oscillation of about 1.7 °C may be indicated at 13760 ± 290 cal yr BP (598 cm), but due to age-depth model uncertainties it is difficult to determine which oscillation this may represent.

At the beginning of the YD, C-IT at Abernethy Forest falls by 5.8 °C to 6.8 °C and remains relatively stable in the early-YD. At Loch Ashik, C-IT initially falls by 3.0 °C, to a low of 8.2 °C, before falling again in the late-YD to a minimum of 4.2 °C at 11640 ± 300 cal yr BP (573 cm). The YD – Holocene transition is marked by rapidly rising temperatures at both sites. At Abernethy Forest, C-IT increases by 5.6 °C over a core length of 28 cm (about 330 years or 60 years per 1 °C rise) and at Loch Ashik a rise of 8.8 °C occurs over a core length of 9 cm (about 480 years or 55 years per 1 °C rise). At both sites the YD – Holocene temperature increase precedes the rise in LOI values by about 300 years. C-IT reaches around 14.0 °C near the core top at both sites. Minor cold oscillations may be indicated during the early-Holocene at both sites but poor chronological control in the age-depth models in this period prevents correlations with the NGRIP record.

At Loch Ashik all samples have a good fit-to-temperature except those in the late-YD (Fig. 7). This suggests that variables other than temperature may have been influencing the response of the chironomid assemblages at this time and concurs with the CCA results which suggest that the chironomid assemblage may have been responding to a change in lake depth. Most of the fossil samples also have good analogues in the modern calibration set (Fig. 7), although most of those in the early-YD and some in GI-1d have poor modern analogues. At Abernethy Forest most samples have a good fit-to-temperature, except for several in the later part of the Lateglacial Interstadial (Fig. 8). Many fossil samples have poor analogues in the modern calibration dataset, especially those in the early Lateglacial Interstadial, during GI-1b and GI-1a, the late-YD and early-Holocene, and towards the top of the sequence. Nevertheless, although these results imply that inferred temperatures in these poor-analogue parts of the sequence should be treated with more caution than those parts of the sequence with good modern analogues, WA-PLS inference models can perform surprisingly well in no-analogue situations (Birks et al., 2010).

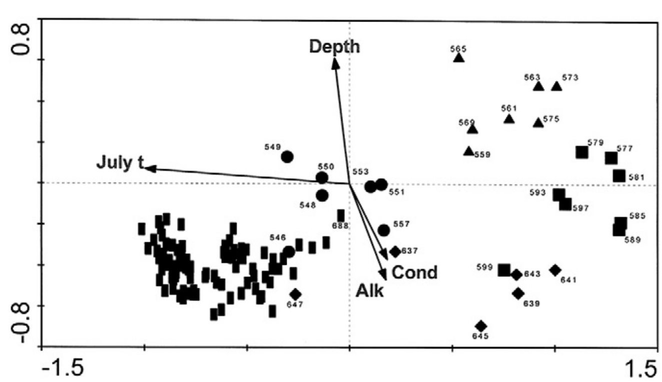

Fig. 6. Fossil samples from Abernethy Forest plotted passively in canonical correspondence analysis (CCA) space of the modern Norwegian calibration dataset. The four significant environmental variables explaining variance in the modern samples are shown as biplot arrows: July *T* (mean July air temperature), Depth (maximum lake water depth), Alk (alkalinity), Cond (conductivity). The number next to each plot denotes the sample depth (cm); diamonds represent samples during GI-1d, squares represent samples during early-YD, triangles represent samples during the late-YD, circles represent samples during YD – Holocene transition, rectangles represent all other samples.

5. Discussion

5.1. Comparison of temperature records

Although general temperature trends during the Lateglacial and early-Holocene in north-west Europe are well-known from pollen, macrofossil and beetle records (e.g. Lowe et al., 1994; Coope et al., 1998; Birks and Ammann, 2000; Walker et al., 2003; Birks and

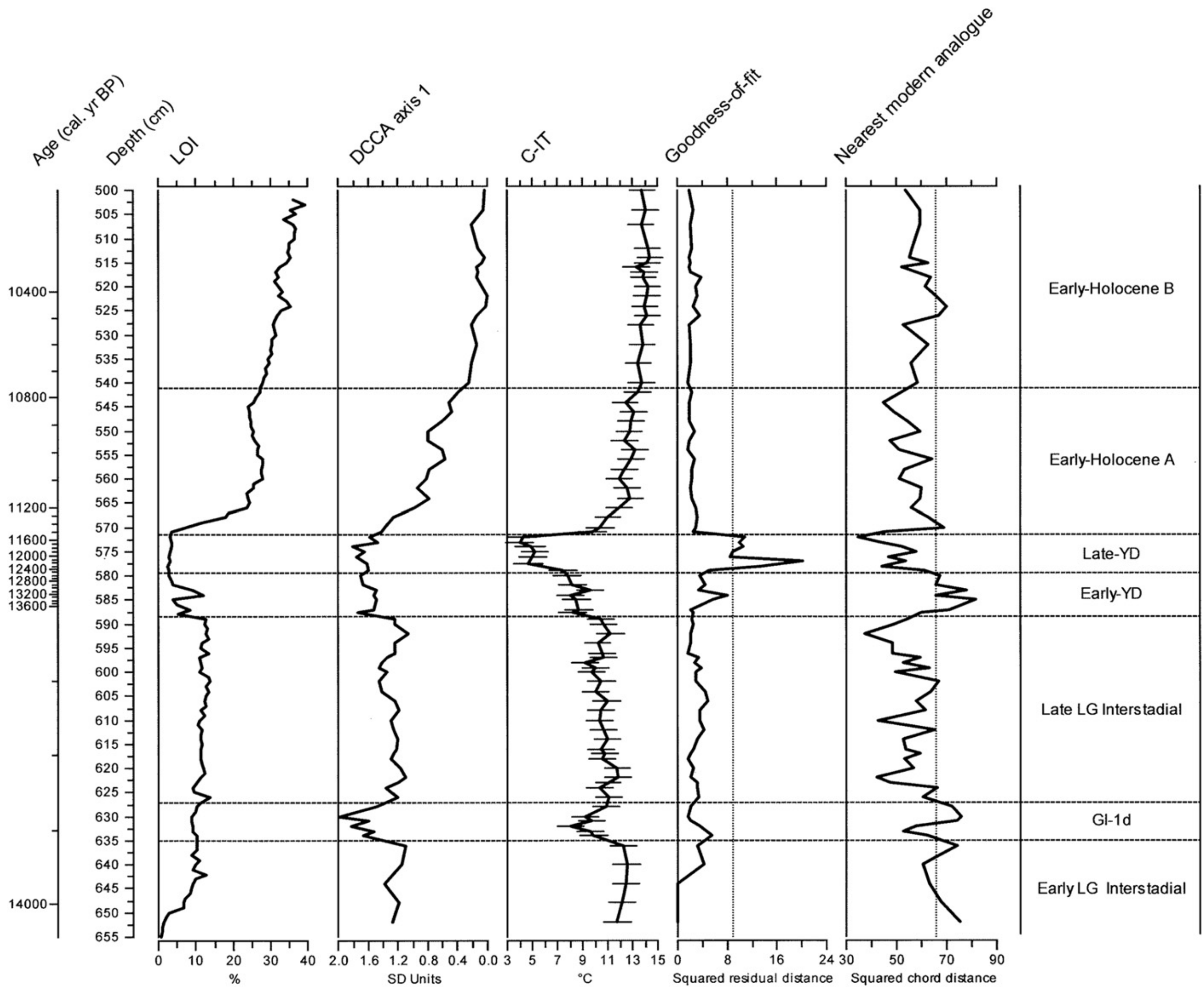

Fig. 7. From left to right, Loch Ashik: organic matter content (as % loss-on-ignition (LOI) at 550 °C); detrended canonical correspondence analysis (DCCA) sample scores in which depth is the only constraining variable; chironomid-inferred temperature estimates (C-IT) with sample specific error bars; goodness-of-fit of the fossil assemblages to temperature, vertical dotted line indicates the 90th percentile of squared residual distances of modern samples to the first axis in a CCA, samples to the right of the line have a poor fit-to-temperature; nearest modern analogue analysis, vertical dotted line indicates the 5th percentile of squared chord distances of the fossil sample to samples in the modern calibration dataset, samples to right of line have no good modern analogue.

Birks, 2008; Bakke et al., 2009) there are relatively few high temporal resolution, quantitative records available. The high resolution Greenland ice-core records (e.g. Rasmussen et al., 2006) provide an indication of mean annual temperature trends. However, they may not exactly match the local climatic trends in north-west Europe. High resolution, quantitative chironomid-inferred Lateglacial and early-Holocene mean July temperature reconstructions are available from Scotland (Brooks and Birks, 2000b), north-west England (Bedford et al., 2004; Lang et al., 2010) and Ireland (Watson et al., 2010; van Asch et al., 2012). Other north-west European records have been published from Norway (Brooks and Birks, 2001) and The Netherlands (Heiri et al., 2007).

Brooks and Birks (2000b) showed that the C-IT trends from Whitrig Bog, in south-east Scotland, closely followed the oxygen-isotope curve of the GRIP ice-core record (Johnsen et al., 1992; Dansgaard et al., 1993) (Fig. 10), although there were differences in the relative magnitude of the Lateglacial Interstadial cold oscillations and in the gradient of the cooling trend through the Lateglacial Interstadial. Unfortunately, the independent timing of events could not be addressed at this site due to restricted chronological information. The timing of events at Whitrig Bog and direct comparisons between Whitrig Bog, Loch Ashik and Abernethy Forest can now be partly addressed by using tephra layers common to all three sites (Fig. 10). Whitrig Bog contains both the Vedde and the Borrobol tephras at core depths 114 cm and 239 cm, respectively (Turney et al., 1997). In the three Scottish sites, the cold oscillation aligned with GI-1d was colder than the cold oscillation during GI-1b, whereas variations in $\delta^{18}O$ in the ice-core records suggest the reverse was likely in Greenland (Figs. 9 and 10). In addition, the GRIP and NGRIP records indicate that the cooling trend through the Lateglacial Interstadial was steeper in Greenland than suggested by the chironomid records from Scotland (Fig. 10). Similar trends are also apparent in the C-IT records from sites in the English Lake District (Bedford et al., 2004; Lang et al., 2010), Lough Nadourcan in north-west Ireland (Watson et al., 2010) and Fiddaun

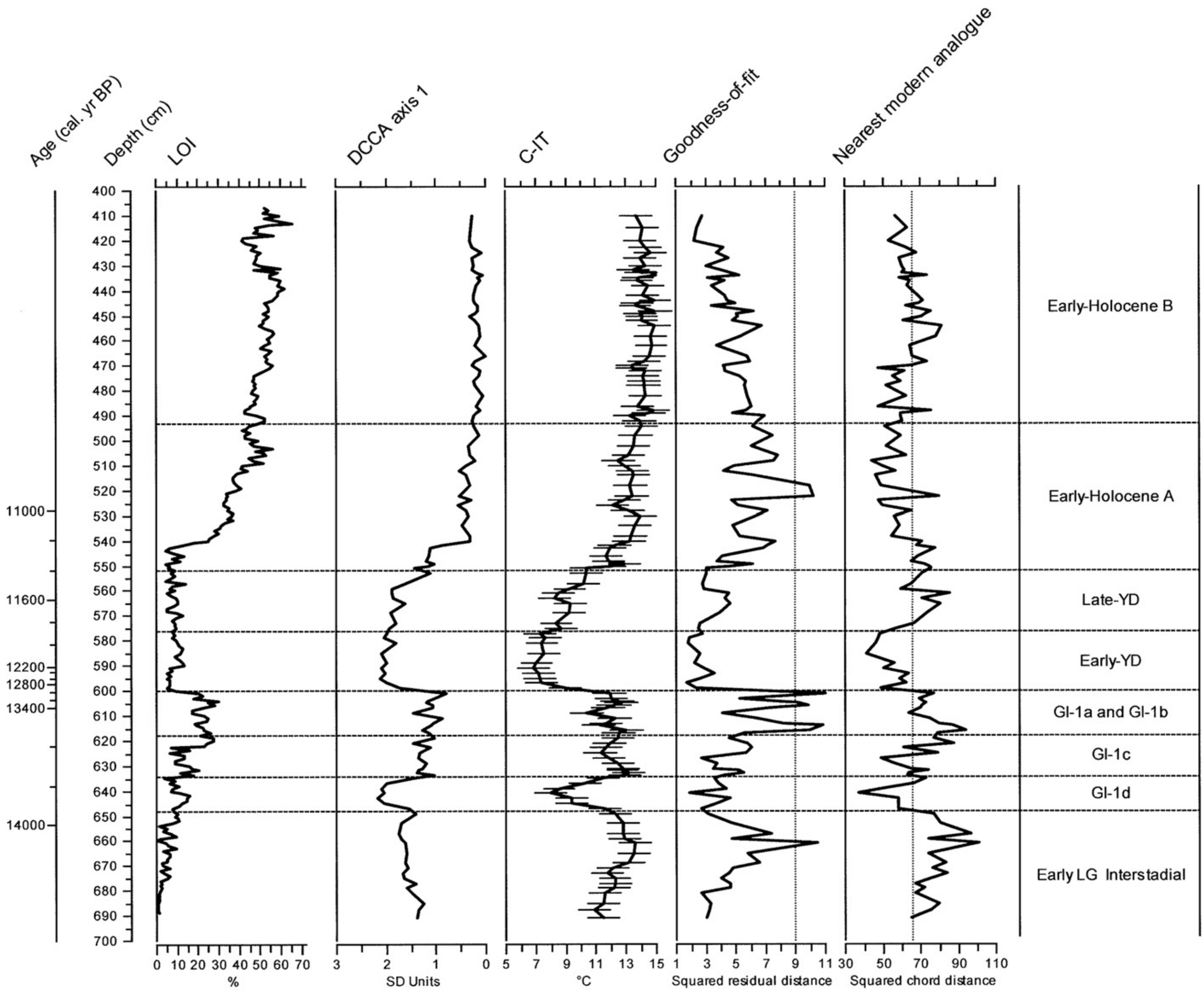

Fig. 8. From left to right, Abernethy Forest: organic matter content (as % loss-on-ignition (LOI) at 550 °C); detrended canonical correspondence analysis (DCCA) sample scores in which depth is the only constraining variable; chironomid-inferred temperature estimates (C-IT) with sample specific error bars; goodness-of-fit of the fossil assemblages to temperature, vertical dotted line indicates the 90th percentile of squared residual distances of modern samples to the first axis in a CCA, samples to the right of the line have a poor fit-to-temperature; nearest modern analogue analysis, vertical dotted line indicates the 5th percentile of squared chord distances of the fossil sample to samples in the modern calibration dataset, samples to right of line have no good modern analogue.

in western Ireland (van Asch et al., 2012). Lang et al. (2010) explored the trends in Lateglacial C-IT at five adjacent lakes in the English Lake District and found the major climate fluctuations at all the sites. However, between-site variance was related to differences in altitude, lake area, and depth. Large, deep lakes at high altitude were found to have the greatest magnitude C-IT changes. Trends similar to these C-IT records are also apparent in the Hawes Water oxygen-isotope record (Bedford et al., 2004). This suggests that the consistent differences between the British chironomid records and the Greenland ice-core records may not necessarily be explained by the latter reflecting annual climate and the chironomid records reflecting summer temperature but that there may be differences in climate development between the regions. The other chironomid records, however, cannot be independently correlated with GI-1d due to limited or imprecise chronological data either through low numbers of radiocarbon determinations, date-sample selection problems (mineral carbon error), small amounts of dateable organic material, or chronologies derived through wiggle-matching regional bio-events (pollen variations).

The unique cold C-IT at Loch Ashik during the final approximately 650 years of the YD contrasts with records from other sites in the region (cited above), which tend to show stable or slightly increasing trends (Fig. 10). In most sites the YD is typically only a little colder than the coldest temperatures attained during GI-1d, whereas at Loch Ashik the later part of the YD is about 4.0 °C colder than GI-1d. The samples from Loch Ashik during this period have a poor fit-to-temperature, which suggests that July air temperature may not have been the main influence on chironomid distribution and abundance at this time. Nevertheless, these samples do have good analogues in the modern calibration dataset so the temperature reconstructions are acceptable. At this time the chironomid fauna was dominated by just two taxa, *M. radialis*-type and *Pseudodiamesa*, together with *Paracladius* and *M. insignilobus*-type at lower abundance. Almost all other taxa were eliminated and head capsule concentrations are extremely low. This suggests that temperature and lake productivity were also extremely low. The closest modern analogues to these samples in the modern Norwegian calibration set all come from cold, relatively deep lakes,

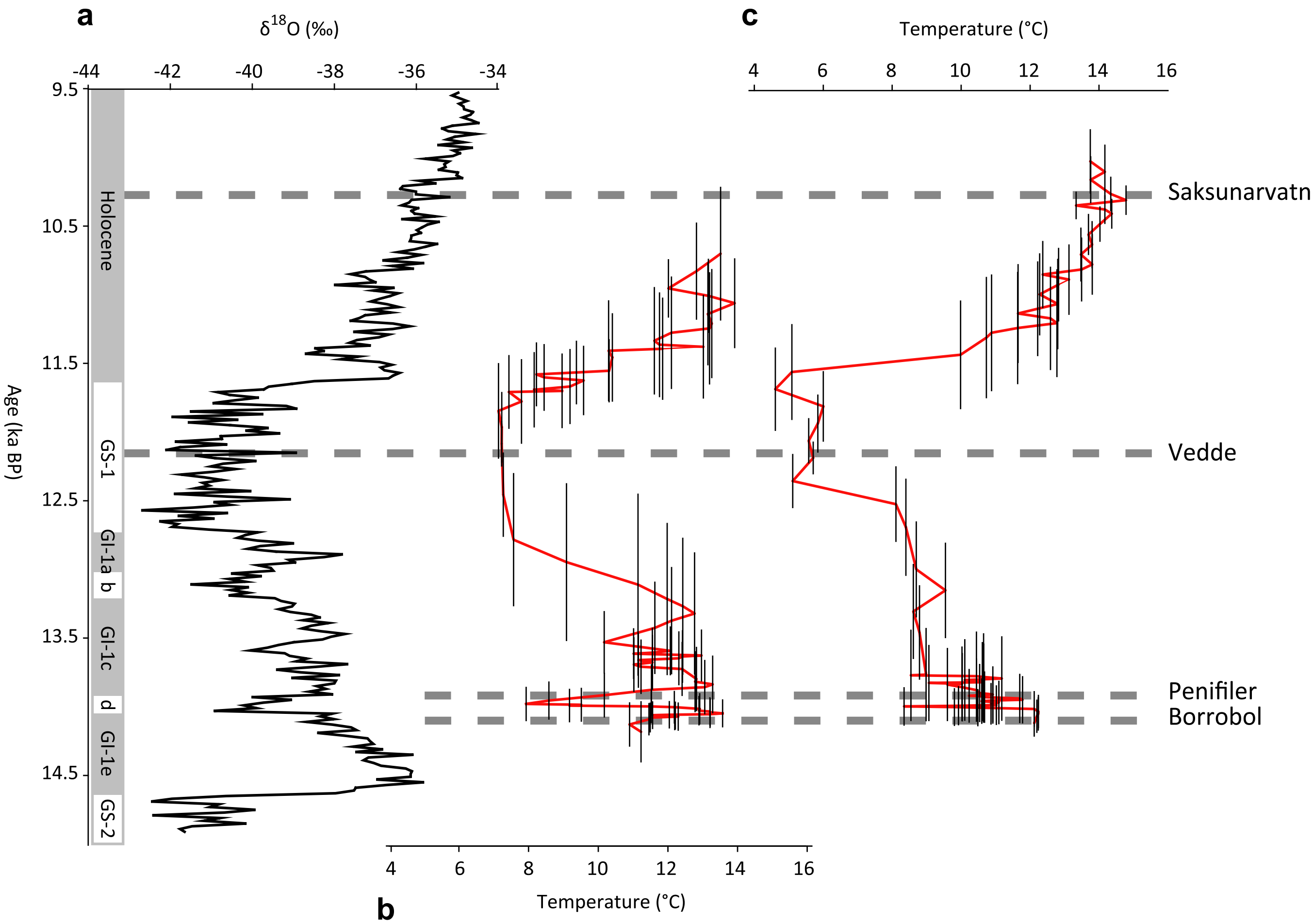

Fig. 9. The Lateglacial and early-Holocene chironomid-inferred mean July air temperature reconstruction (°C) for (b) Loch Ashik and (c) Abernethy Forest compared with (a) NGRIP oxygen-isotope data (from Rasmussen et al., 2006). The chironomid-inferred temperature reconstruction is presented as mid-point ages with corresponding 95.4% ranges presented as error bars, while the NGRIP time-scale is in GICC05 ice-core years BP. The occurrence of the Vedde, Saksunarvatn, Borrobol, and Penifiler tephras are marked by grey dashed lines. The INTIMATE Greenland Event stratigraphy is listed below the NGRIP oxygen-isotope data (Lowe et al., 2008). The general GI-1, GS-1, and Holocene trend can be observed in all records as can a cold oscillation coincident with GI-1d.

at high altitude or latitude, and having low conductivity and alkalinity (Brooks and Birks, 2000a, 2001; 2004; unpublished data). When the Loch Ashik samples are plotted passively in CCA space of the modern Norwegian calibration dataset (Fig. 5) the composition of the chironomid assemblage in the late-YD samples is clearly different from the other samples in the sequence, possibly reflecting the extreme environmental conditions at this time.

An ice-field occupied the Skye mountains during the YD which Ballantyne (1989) suggested covered 155 km^2. Golledge (2010) shows that the eastern perimeter of this ice-field was about 10 km from Loch Ashik. Therefore, the close proximity of this ice-field and the influence of catabatic winds may have depressed air temperature (Levesque et al., 1997) supposing that the ice-field expanded due to increased winter precipitation during the last 600 years of the YD. Although the timing of maximum glacial extent cannot be confirmed on Skye, at Loch Lomond and Lochaber, in the Scottish Highlands, the YD ice-field reached its greatest extent late in the YD around 12000 cal yr BP due to increased winter precipitation and cold temperatures (MacLeod et al., 2011). Increase in winter precipitation may also have resulted in the expansion of long-lasting snow beds in the catchment of Loch Ashik resulting in cold melt-water entering the lake. Conversely, YD ice-fields in the Cairngorms were relatively small and distant from Abernethy Forest (Golledge, 2010). Benn and Ballantyne (2005) calculated precipitation values in eastern and western Scotland at the end of the YD and suggest that precipitation values in the eastern Highlands were little different from the present day, whereas in north-west Scotland precipitation was 500–1600 mm yr^{-1} greater than present. Interestingly, CCA results suggest that the lake level at both Loch Ashik and Abernethy Forest may have risen during the late-YD (Figs. 5 and 6). However, this seems less likely at Abernethy Forest as the high percentages of *Artemisia* pollen in the Cairngorms during the Younger Dryas suggest the prevalence of a relatively arid climate (Birks and Mathewes, 1978). *Artemisia* pollen was considerably less abundant on Skye at this time (Birks, 1973; Walker and Lowe, 1991). The increase in precipitation levels in the west and the steeper west-east precipitation gradient during the YD probably resulted from atmospheric chilling by the West Highland Icefield and consequent reduction of snow carried by the westerly air masses to the Cairngorms (Benn and Ballantyne, 2005).

The rapid warming temperature trends in the early-Holocene inferred at Loch Ashik and Abernethy Forest are followed by more gradual warming until temperatures exceed those inferred in the Lateglacial Interstadial. This is consistent with the Greenland ice-core records and other British chironomid records (cited above).

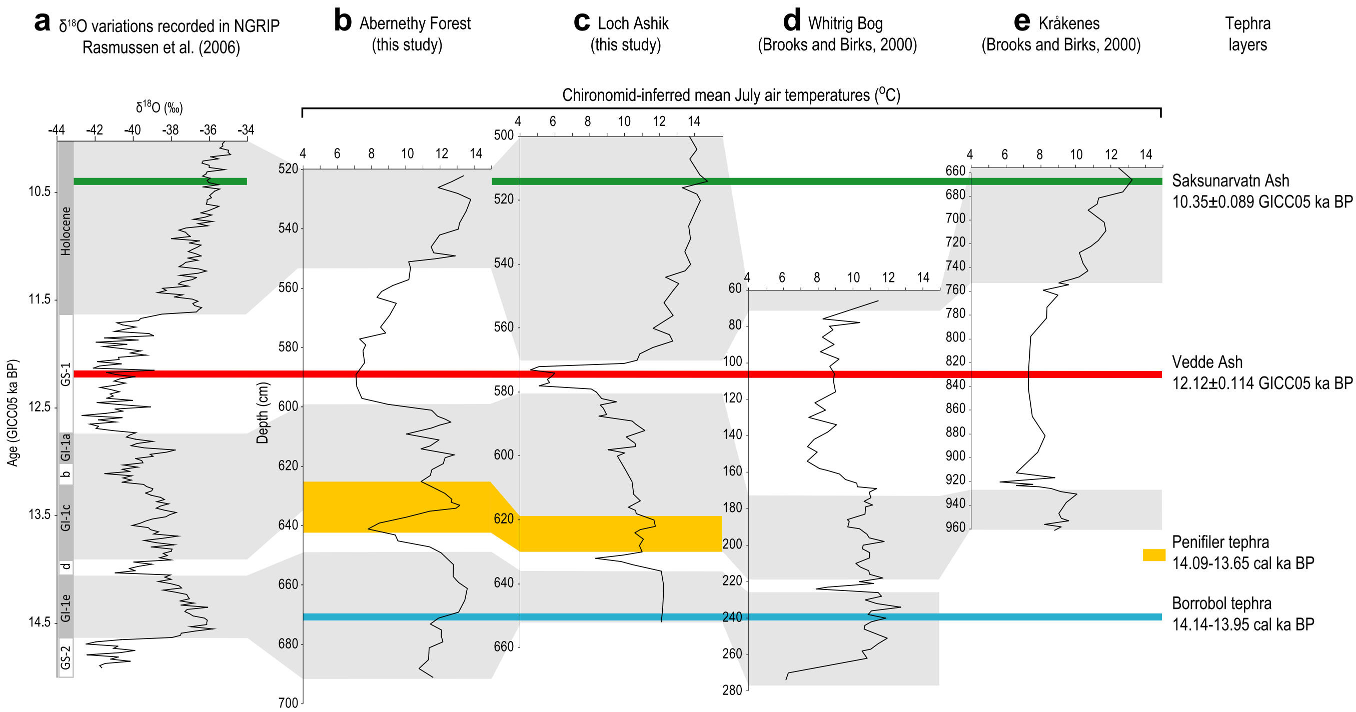

Fig. 10. Chironomid-inferred mean July air temperature (C-IT) reconstructions (°C) across Northern Europe from sites reported to contain common tephra layers compared with the NGRIP oxygen-isotope data (a) (from Rasmussen et al., 2006). C-IT data are presented against depth (cm) as the Whitrig Bog record (d) has insufficient chronological information to construct a robust age model. The *y*-axis of each site (depth cm) has been scaled so that the tephra layers align against their chronological position in the NGRIP record. Grey shading is used to mark the main chronostratigraphical boundaries (based on the INTIMATE Event stratigraphic scheme of Lowe et al., 2008) in each record. The oscillations observed within the later part of GI-1 appear to be represented in each record; however, the age models developed for these sites are not yet sufficiently precise to link the events directly.

The absolute C-IT values inferred at Loch Ashik and Abernethy Forest are also similar to those inferred at the other British sites in most parts of each sequence.

Comparison of the British C-IT records with the two published NW European LGIT chironomid records reveals broad agreement but also some differences (Brooks and Birks, 2000a; Heiri et al., 2007). At Kråkenes, western Norway, (Brooks and Birks, 2000a) the Lateglacial Interstadial is truncated at the base due the late withdrawal of ice and so highest temperatures are not reached until the end of the Lateglacial Interstadial and the GI-1d and GI-1b cold oscillations are not apparent (see also Birks et al., 1994; Lowe et al., 1994). In the YD, C-IT is about 3 °C cooler than in the Lateglacial Interstadial, a warming trend is apparent in the YD, and early-Holocene temperatures climb steeply to reach values about 3 °C higher than peak temperatures in the Lateglacial Interstadial. Table 3 shows C-IT from Abernethy Forest, Loch Ashik, Whitrig Bog, and Kråkenes at the levels of tephra deposits and the temperature trends at these sites are compared in Fig. 10, which shows that climate development was similar at all these sites during the LGIT. Holocene and Lateglacial Interstadial temperatures at Kråkenes are cooler than the Scottish sites, probably reflecting the more northerly location and extremely oceanic climate of the site (present mean July air temperature at Kråkenes is 12.6 °C, about 2 °C cooler than present at Loch Ashik). The temperatures inferred at Loch Ashik during the late-YD are about 0.5 °C lower than those at Kråkenes, which was receiving melt waters from a cirque glacier in its catchment (Birks et al., 2000), may be due to the proximity of Loch Ashik to the large Skye ice-field.

In contrast to the British records, C-IT records from Hijkermeer, The Netherlands (Heiri et al., 2007), indicate that Lateglacial Interstadial peak temperatures were not attained until after GI-1d. In addition, cooling correlated with GI-1b was stronger than cooling associated with GI-1d. These trends are consistent with other palaeoclimate records from central Europe (Heiri and Millet, 2005; Magny et al., 2006; Ilyashuk et al., 2009; Larocque-Tobler et al., 2010) and suggest regional differences in the influence of atmospheric and oceanic circulation on European climate, probably reflecting the stronger influence of the North Atlantic Current on Scottish and Norwegian sites.

5.2. Lake ecology and faunistics

In the Abernethy Forest sequence there is an absence of certain cold stenotherms which are present at Loch Ashik, such as *Paracladius*, and a low abundance of others, such as *Pseudodiamesa*, which are much more abundant at Loch Ashik. This may account for the lower compositional turnover in response to the YD at Loch Ashik, as revealed by DCCA, since the fossil assemblage already included a prevalence of cold-adapted taxa during the Lateglacial Interstadial, which continued into the YD. At Abernethy Forest the cold stenotherms colonized the lake during the cold GI-1d oscillation and YD but were absent during warmer intervals in the Lateglacial Interstadial.

Throughout most of the Lateglacial and early-Holocene, C-IT is higher at Abernethy Forest than Loch Ashik, which may be a consequence of its more continental climate resulting in warmer summers. LOI is also generally higher at Abernethy Forest, perhaps reflecting higher organic productivity or less mineral inwash or autogenic silica production (Birks and Birks, 2006). The head capsule concentrations were generally lower and more constant at Abernethy Forest, except in the YD when they were extremely low at Loch Ashik, probably reflecting the extremely cold, unproductive environment and possibly long-lasting winter ice-cover. Despite the cooler conditions at Loch Ashik, chironomid diversity was higher throughout the sequence than at Abernethy Forest, although many taxa occur in both lakes.

Table 3
Comparison of chironomid-inferred mean July air temperature at Abernethy Forest, Loch Ashik, Whitrig Bog and Kråkenes at times of tephra deposits.

Tephras	Sites			
	Abernethy Forest	Loch Ashik	Whitrig Bog	Krakenes
Saksunarvatn (10347 ± 89 GICC05 yr BP)	x	14.0 °C	x	11.9 °C
Ashik tephra (precise age unknown)	x	12.8 °C	x	x
Vedde (12,171 ± 114 GICC05 yr BP)	7.8 °C	5.8 °C	8.9 °C	6.4 °C
Penifiler (14.09–13.65 cal ka BP)[a]	7.8–11.4 °C	8.3–11.8 °C	x	x
Borrobol (14.14–13.95 cal ka BP)	12.2 °C	12.1 °C	11.9 °C	x

[a] The Penifiler tephra has a relatively large vertical distribution in Abernethy Forest and Loch Ashik. Matthews et al. (2011) demonstrated this tephra layer is closely associated with upper boundary of a cold oscillation correlated with GI-1d. At Loch Ashik the Penifiler tephra slightly post-dates a similar oscillation and thus it is suggested the Penifiler tephra just post-dates this event. The temperatures present here reflect this slight uncertainty and are presented as a range of temperatures from the coldest point of the oscillation and the return to warmer temperatures.

In both sequences, most changes in sediment lithology do not coincide with significant changes in chironomid assemblage composition (Figs. 3 and 4). This suggests that chironomids were not responding to changes in the lake-sediment but that an external driver (i.e. changes in temperature) was causing these changes in the chironomid assemblages. The difference in timing between sedimentological change and chironomid assemblage change is most apparent at the end of the YD at Abernethy Forest where the C-IT begins to rise at a core depth of 575 cm, about 30 cm before there is a change in the sediment lithology and LOI.

The increase in abundance of the thermophilic taxon *Heterotanytarsus apicalis*-type at both sites towards the tops of the sequences is probably a response to Holocene warming. However, this species is also indicative of dissolved organic carbon in the water and its higher abundance at Loch Ashik may reflect a greater development of peat surrounding the loch. Only later did the Abernethy site become overgrown by bog.

5.3. Comparison with pollen records

Both Loch Ashik and Abernethy Forest have been designated as key reference sites for the LGIT on the basis of their highly resolved pollen records. Therefore, the C-IT records now available for these sites are invaluable for placing these pollen records in an improved climatic context. The Loch Ashik pollen record (Walker and Lowe, 1991) reflects the rapid warming at the start of the Lateglacial Interstadial, followed by gradual climatic cooling, the return of arctic-like vegetation during the YD, and the rapid warming in the early-Holocene. In addition, during a period correlated with GI-1d, declines in *Juniperus* and *Empetrum*, and increases in *Rumex* and *Salix* were probably in response to the 4 °C summer cooling inferred from the chironomid assemblages. Although there are some similarities between the pollen sequences at Loch Ashik and Abernethy Forest, the percentages of *Artemisia* pollen in the Younger Dryas are higher at Abernethy Forest suggesting that the climate may have been more arid (Birks and Mathewes, 1978). A vegetation response to the GI-1d cooling is not apparent in the pollen record at Abernethy Forest possibly because an ecological threshold was not passed, or the sample resolution was too low to detect short-term changes.

5.4. Comparison with beetle records

Coleoptera have been used to infer the mean temperature of the warmest and coldest months during the Lateglacial and early-Holocene at several sites in north-west Europe, including some in Scotland (Lowe et al., 1994; Coope et al., 1998). The temperature trends are similar to those inferred from chironomids, although the beetle records lack the high temporal resolution of our chironomid stratigraphies. Coleoptera-inferred early-Lateglacial Interstadial temperature estimates for southern Scotland peak at 16–17 °C, which is about 3–4 °C higher than maximum chironomid-inferred temperatures, and falls outside the range of C-IT prediction errors. Later in the Lateglacial Interstadial Coleoptera-inferred temperatures range from 10 to 14 °C, which is encompassed by the range of those derived from chironomids. During the YD, Coleoptera-inferred temperature estimates from two sites in southern Scotland are 8.5 °C, about 1.0–1.5 °C warmer than the chironomid-inferred estimates from Whitrig Bog (Brooks and Birks, 2000b) and the early-YD at Abernethy Forest, although within the range of C-IT error estimates, but they are similar to the Loch Ashik estimates in the first part of the YD.

6. Conclusions

The high resolution, low uncertainty, chironomid-inferred July air-temperature reconstructions from Loch Ashik and Abernethy Forest provide important, independently dated, records of climate change during the Lateglacial and early-Holocene in Scotland, and provide a context for the previously reported vegetational changes at these two key reference sites. The age-depth models developed for Abernethy Forest and Loch Ashik allow independent comparisons to be made with the Greenland ice-core records. It is most likely that cold oscillations in the Scottish Lateglacial Interstadial were synchronous with oscillations GI-1d and GI-1c in the NGRIP record. However, poor dating control in both Scottish records precludes comparison of the relative timing of oscillation GI-1b. For similar reasons there are large discrepancies in the dates of the YD – Holocene boundary. The general similarities in most of the trends between these two Scottish sites, Norwegian records, and ice-core records from Greenland emphasise the widespread nature of the temperature changes in the eastern North Atlantic region. The most important driver of these changes is probably fluctuations in the North Atlantic thermohaline circulation (Bakke et al., 2009). Nevertheless, consistent differences between British and Greenland records, and also those from The Netherlands and central-southern Europe (Heiri and Millet, 2005; Ilyashuk et al., 2009), indicate that there are variations in the responses to climate drivers at the local level and highlight the importance of high resolution and precise chronologies to make detailed temporal comparisons of events in space. The key findings identified within our new Scottish records are:

1. A strong cold oscillation during the Lateglacial Interstadial has been identified in both records, which appears to be synchronous with GI-1d in the GICC05 ice-core records. This is the highest amplitude oscillation detected during the Lateglacial

Interstadial in both sequences. Comparison of the magnitude of this event in other British and European proxy records suggests regional climate variability. Although this oscillation appears to be synchronous with GI-1d, there are still chronological uncertainties regarding the timing of its onset and absolute duration in our records. These uncertainties cannot be resolved here and require further chronological refinement at sites that offer higher (decadal or annual) resolution. However, our results currently provide the best independent timing for this oscillation in Britain and strongly suggest that it correlates with Greenland GI-1d.

2. The differences in C-IT observed between Loch Ashik and Abernethy Forest in the late part of the Younger Dryas may indicate differences in local climate drivers. These local differences are important in understanding terrestrial environmental responses to regional climatic forcing as shown by Lang et al. (2010).
3. The reconstructed C-IT for the basal sediments at Loch Ashik and Abernethy Forest are between 12 °C and 13 °C indicating that the lakes may not have been open for colonisation before the rise in temperatures in the early deglacial phase. This might reflect the timing of the withdrawal of ice from the regions, placing it after the initial Lateglacial Interstadial warming but prior to the deposition of the Borrobol tephra (14.14–13.95 cal ka BP).
4. Making robust comparisons between C-IT reconstructions across Europe is made more complicated by chronological uncertainties associated with each record. The identification of tephras in sequences can provide isochronous markers which facilitate direct chronological comparisons. At sites where this has been achieved, similarities in the timing of temperature trends are apparent in Greenland, Scotland and Norway.

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