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Corresponding Author: Mr Stephen Brooks,

Corresponding Author's Institution: Natural History Museum

First Author: Stephen J Brooks

Order of Authors: Stephen J Brooks; Peter G Langdon

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Abstract: We present a series of summer air temperature isotherm maps based on chironomid-inferred temperatures from northwest Europe, covering the Lateglacial and early Holocene (15-8 ka BP). These maps are the first of their kind, and use data derived from 22 Lateglacial sites and 34 early Holocene sites. The isotherms are generated by weighted spatial interpolation (kriging). The major patterns of chironomid-inferred summer temperatures are spatially well-resolved in both the Lateglacial and early Holocene. The isotherm maps indicate that there was a strong west to east gradient during the Lateglacial Interstadial (GI-1) due to the influence of thermohaline circulation in the regions bordering the north Atlantic, which diminishes eastwards. A strong north to south temperature gradient is also apparent, particularly in eastern regions, influenced by the extent of the Scandinavian ice-cap. Peak temperatures are achieved early in the Interstadial in the south of the region but occur towards the end of the Interstadial in the north. Holocene warming varies spatially and temporally and is earliest in the south and east, but later in the north and west. During the period covered in our study maximum warmth is reached ca. 10 ka BP. The chironomid-based Lateglacial isotherm maps are compared with previously published isotherm maps from the same region based on beetle-inferred temperatures. While the trends shown in the two datasets are similar, beetle-inferred temperatures are often warmer than chironomid-inferred temperatures. This is especially marked in GI-1e and may be due to microclimatic effects causing the chironomids to underestimate air temperatures and/or the beetles to over-estimate air temperatures. The spatial coherence between sites in both the Lateglacial and early Holocene suggest that the chironomid-based temperature estimates are largely reliable, although data testing suggests that estimates from southern Scandinavia may be less reliable perhaps due to high topographical relief influencing local climate. More data points are required, particularly from northwest Scotland, southwest England and Wales, northeast France, Denmark, Finland and the Baltic States, to confirm trends and provide even coverage and a denser network of sites.

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Signed by all authors as follows:

S J BROOKS

P G LANGDON

Norm Catto
Editor-in-Chief
Quaternary International
Dept of Geography
Memorial University
St. John's NL A1B 3X9
Canada

09 December 2013

Tel: 0207 942 5198
Fax: 0207 942 5229
E-mail: sjb@nhm.ac.uk

Dear Norm,

Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15-8 ka BP) inferred from chironomid assemblages

Stephen Brooks and Peter Langdon

Please consider the above revised manuscript which I have resubmitted, incorporating responses to reviewer's comments, for publication in *Quaternary International*. This manuscript is intended for the "*Russell Coope Honorary volume*".

Yours sincerely,

Stephen Brooks
Research Entomologist

Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15-8 ka BP) inferred from chironomid assemblages

Stephen J. Brooks, Department of Life Sciences, Natural History Museum, London SW7 5BD, UK

Peter G. Langdon, Geography and Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK

Abstract

We present a series of summer air temperature isotherm maps based on chironomid-inferred temperatures from northwest Europe, covering the Lateglacial and early Holocene (15-8 ka BP). These maps are the first of their kind, and use data derived from 22 Lateglacial sites and 34 early Holocene sites. The isotherms are generated by weighted spatial interpolation (kriging). The major patterns of chironomid-inferred summer temperatures are spatially well-resolved in both the Lateglacial and early Holocene. The isotherm maps indicate that there was a strong west to east gradient during the Lateglacial Interstadial (GI-1) due to the influence of thermohaline circulation in the regions bordering the north Atlantic, which diminishes eastwards. A strong north to south temperature gradient is also apparent, particularly in eastern regions, influenced by the extent of the Scandinavian ice-cap. Peak temperatures are achieved early in the Interstadial in the south of the region but occur towards the end of the Interstadial in the north. Holocene warming varies spatially and temporally and is earliest in the south and east, but later in the north and west. During the period covered in our study maximum warmth is reached ca. 10 ka BP. The chironomid-based Lateglacial isotherm maps are compared with previously published isotherm maps from the same region based on beetle-inferred temperatures. While the trends shown in the two datasets are similar, beetle-inferred temperatures are often warmer than chironomid-inferred temperatures. This is especially marked in GI-1e and may be due to microclimatic effects causing the chironomids to underestimate air temperatures and/or the beetles to over-estimate air

temperatures. The spatial coherence between sites in both the Lateglacial and early Holocene suggest that the chironomid-based temperature estimates are largely reliable, although data testing suggests that estimates from southern Scandinavia may be less reliable perhaps due to high topographical relief influencing local climate. More data points are required, particularly from northwest Scotland, southwest England and Wales, northeast France, Denmark, Finland and the Baltic States, to confirm trends and provide even coverage and a denser network of sites.

Key words European isotherm maps; mutual climatic range; chironomids; beetles; Lateglacial; Holocene

Introduction

Reliable estimates of past temperature trends at a regional scale are essential if the processes that drive climate change are to be understood. Temperature reconstructions from a period such as the transition from the Lateglacial to early Holocene, when the climate underwent rapid, high amplitude fluctuations, are especially valuable if we are to predict accurately how the climate might change in the future. Of particular interest are studies of climate development from regions such as northwest Europe. Here the climate is influenced by multiple feedbacks and forcing mechanisms, including variations in the North Atlantic thermohaline circulation (THC), sea- and land-based ice sheets, vegetation type and cover, and solar insolation. This leads to complex shifts in geographical temperature gradients, seasonality and uneven rates of temperature change both spatially and temporally.

There are relatively few proxies that can generate the quality of quantitative temperature data required to provide a regional view of climate change in northwest Europe during the Lateglacial to early Holocene transition at high temporal resolution. Among the most suitable temperature proxies are Coleoptera (beetles) and Chironomidae (non-biting midges) (Elias 2010; Brooks, 2006; Walker and Cwynar, 2006). High quality beetle-inferred temperatures of the warmest month have been available from many sites throughout northwest Europe since the development of the mutual climatic range (MCR) method by Atkinson *et al*. (1987). Temperature records derived from chironomid assemblages have become available more recently since the development of the transfer function method (Walker *et al*., 1991).

Both beetles and chironomids occur at high diversity in freshwater sediment samples and many species are characteristic of particular climate regimes. Chironomids are abundant in lake sediments and hundreds of individuals are frequently present in just a few grams of sediment. For this reason sufficient numbers can be obtained from sediment cores sliced at fine intervals to produce consecutive, high temporal resolution temperature sequences (Quinlan and Smol, 2001; Heiri and Lotter, 2001; Larocque, 2001). Beetle remains, on the other hand, occur less frequently and so larger quantities of sediment are required for analysis. In many British sites these are typically obtained from sections dug from old lake beds or river channels.. As a result beetle-inferred temperature records are often at relatively coarse resolution, encompass a large time-slice, and may not be analysed in consecutive samples. The relative paucity of beetle remains in sediment samples means that species abundance is not taken into account when temperature is estimated from an assemblage. Instead each species present in the sample is given equal weight. The method for estimating temperatures has subsequently been refined to make MCR estimates more reliable by including ubiquity analysis (Bray *et al*., 2006) to provide a better model of climate space occupied by a species, and jackknifing techniques to provide an estimate of the standard error of the MCR (Buckland 2007). The MCR method relies on knowledge of the modern distribution in climate space of each species in the fossil assemblage. A climate envelope for each species is estimated based on T_{range} (the difference between the mean temperature of the warmest month and the mean temperature of the coldest month) and T_{max} (the mean temperature of the warmest month). A palaeotemperature (e.g. T_{max}) can then be inferred from the overlap of the climate envelopes of each species in the fossil beetle assemblage (Atkinson *et al*., 1987). Only carnivorous and scavenging species are used in the estimate as phytophagous species may simply reflect the distribution of the beetle's food plant. Obviously, only fossil species that occur in the modern calibration set can be used for the temperature inference and as many as half the fossil species may, therefore, have to be discarded. The temperature estimates thus generated provide a range of possible temperatures, all of them equally likely, although often only the median temperature in this range (calibrated to correct a persistent bias) is quoted (Coope *et al*., 1998).

Because chironomids can be recovered from lake sediment samples in high numbers, the abundance of each taxon in the fossil assemblage is taken into account when estimating the palaeotemperature. Only summer temperatures can be estimated from chironomid assemblages because, in northwest Europe, adults of most species are not present during the winter and the aquatic larvae are insulated from winter air temperatures below a layer of ice on the lake surface. Modern temperature calibration sets have been developed across long temperature gradients based on the collection of lake surface sediments, which include a representative sample of the modern chironomid assemblage (Brooks, 2006). From these datasets the temperature optimum of each chironomid taxon can be modelled based on the weighted average of its abundance in each lake (Juggins and Birks, 2012). Estimates of summer palaeotemperatures are derived by taking an abundance-weighted average of the temperature optima of the taxa in the fossil assemblage. Typically, at least 90% of the taxa in the fossil assemblage are used in the temperature reconstruction because the location of the modern calibration set is typically from the same region as the fossil site. Bootstrapped sample specific errors, expressed as two standard deviations from the mean, are obtained for each temperature estimate. The performance of both MCR and transfer function methods is assessed by comparing predicted temperature, derived from a modern assemblage not used in the modern calibration sets, against observed temperature measured at nearby meteorological stations. There are few published examples of comparisons between beetle-inferred and chironomid-inferred summer air temperature estimates from the same site (e.g. Lemdahl, 2000). However it is important to make such comparisons as these may highlight biases in the methods and also provide a means of validating the temperature estimates.

Transfer function methods have recently been criticised by Juggins (2013), who argues that if transfer functions contain confounding variables, especially those co-varying with the variable of interest and which act as secondary gradients, then models will not be transferable between regions. Users would be mistaking surrogacy for ecological effects and past changes in secondary variables may lead to spurious reconstructions of the variable of interest. If models are not transferable between regions, then it is a large leap to suggest they are transferable over time. The work undertaken by Juggins (2013) focussed on diatom calibration sets and transfer functions, although these potential problems could affect transfer functions based on any proxy. Discussions concerning how well chironomids can reconstruct temperature have been aired most recently by Velle *et al*. (2010; 2012) and Brooks *et al*. (2012a). Furthermore, Holmes *et al*. (2011) have argued that combining local and extra-regional calibration sets can improve the accuracy of temperature reconstructions. To date no one has used chironomid-inferred temperatures to assess spatial variability in temperatures over long timescales. Our approach uses this method to assess the spatial robustness of chironomid-inferred summer temperatures from the Lateglacial to early Holocene across north-west Europe.

Coope *et al*. (1998) summarised, in a series of isotherm maps, Lateglacial – Holocene transition beetle-inferred MCR summer air temperature data from 77 sites across northwest Europe. The maps were arranged in eight time-slices, reflecting the major climatic events during this period. Many of the 77 datasets did not cover the entire Lateglacial – Holocene transition period and several were single records representing a snap shot during this period. As a result between 8 and 33 records were available for each time slice, which is broadly comparable with our chironomid dataset. On each map, the inferred temperature for each site during the relevant time-slice was plotted and isotherms were generated by linking records in 2°C classes using visual spatial interpolation.

Since 1998 chironomid-inferred mean July air temperature records have become available and there are now 22 records from northwest Europe covering the Lateglacial – Holocene transition, and 34 records covering the early Holocene, up to 8 ka BP (Fig 1). This now provides the first opportunity to compare northwest European regional temperature estimates between these two proxies using isotherm maps. Isotherm maps provide an easily assimilated summary of temperature trends and gradients across Europe, during this period of rapid, high amplitude climatic change.

Methods

Chironomid-inferred mean July air temperature estimates (C-IT) for all the Lateglacial sites were generated from a modern calibration set of 153 Norwegian lakes (Brooks and Birks, 2000; 2001; 2004; unpublished), covering a mean July air temperature range of 3.5-16.0°C, and including 143 chironomid taxa. The 2-component WA-PLS inference model has a root mean squared error of predication ($RMSEP_{jack}$) of 1.01°C, an r^2_{jack} of 0.91 and a maximum bias of 0.93°C. The Norwegian-based inference model is the most appropriate for this study because i) it is well-suited to infer temperatures within the range of temperatures expected in northwest Europe during the Lateglacial – Holocene transition; ii) it includes all the major taxa present in the fossil sequences; iii) the fossil lakes are similar in type to those in the modern Norwegian calibration set. New temperature reconstructions were performed for those sites in which different inference models had originally been used to generate the published data. The Norwegian inference model was also used for the majority of the early Holocene sites. However, a model based on a modern Icelandic calibration set (Langdon *et al*., 2008) was the most appropriate for the Holocene Icelandic fossil sequences. In addition a modern Swedish calibration set (Larocque *et al*., 2001) was used to infer temperatures from some of the Holocene Swedish sites and a modern Finnish calibration set (Olander *et al*., 1999) was used for some of the Holocene Finnish sites because of taxonomic incompatibility between the Swedish and Finnish fossil data and the Norwegian calibration set. Use of the Norwegian inference model for the all the Late-glacial sequences has the advantage of removing any bias that may be introduced by using different transfer functions. However, there are also some advantages in using different calibration sets for the early Holocene samples as this provides a means of testing for any inherent regional biases in the local inference models.

The data for the beetle-inferred temperatures of the warmest month (B-MCR) were taken from Coope *et al*. (1998). The B-MCR data used are 'calibrated' (see Coope *et al*., 1998 for explanation) median values of the total MCR from a series of MCR estimates, although any temperature within the MCR is equally likely. Coope *et al*. (1998) do not provide information on the MCR range for each data point or how many temperature estimates were used for each time slice. Most of the chironomid sequences used in our study cover the entire Lateglacial – Holocene transition, although some do not include the early part of this period because the sites were still under the Scandinavian ice-sheet. Each plotted C-IT value is derived from a continuous sequence and is the mean C-IT for each particular time slice. The C-IT values used in the isotherm maps do not include sample specific errors, but these are typically about 1.0-1.2°C.

The chironomid isotherm maps were developed using spatial interpolation analyses in ArcMap (ArcGIS). Three techniques were tested: kriging, inverse distance weighting (IDW), and spline functions. The number of data points was too few to use splines, as this approach drops a mesh around the data points to aid interpolation. With relatively few data points unrealistic values were interpolated at the edges of the maps. Comparisons between kriging and IDW revealed a mean difference of 0.84°C for the Lateglacial maps, with only the GI-1d and GI-1e time slices having mean differences > 1°C, but both were < 2°C (Fig 2). The sites for these time slices are generally clustered relatively close together, however, Jansvatnet, in the extreme north of Scandinavia, was remote from other sites and this is the most likely reason for the different results between the two interpolation techniques. When Jansvatnet is removed from the interpolation, and the rasters differentiated, the average difference drops to 0.25°C (Fig 2). This analysis shows that outliers can have a large effect on the raster output, although the effect is influenced by which interpolation technique is used. Based on the results of these analyses, we used kriging to generate the isotherm maps for each time slice.

We used 14 time-slices covering the period 15-8 ka BP. Seven time-slices cover the Lateglacial (GS-2 before 14.7 ka BP, GI-1e 14.7-14.1 ka BP, GI-1d 14.1-13.9 ka BP, GI-1c 13.9-13.3 ka BP, GI-1b 13.3-13.1 ka BP, GI-1a 13.1-12.9 ka BP, and GS-1 12.9-11.7 ka BP), and these are directly comparable with those used by Coope *et al*. (1998) and reflect the Greenland ice core event stratigraphy (Bjorck *et al*., 1998). Where a core chronology was not available, the C-IT curves were wiggle-matched against the NGRIP ice core oxygen isotope record (North Greenland Ice Core Project members, 2004) and allocated to the appropriate time slice. Seven time-slices cover the early Holocene (11 ka, 10.5 ka, 10 ka, 9.5 ka, 9 ka, 8.5 ka, and 8 ka BP). All ages are reported as calibrated radiocarbon ages. The C-IT used for each 500-year time-slice is averaged for this period, and each record is based on a radiocarbon chronology constructed for each site. Holocene radiocarbon chronologies typically have multi-centennial levels of uncertainty (Blockley *et al*., 2007), and thus, by treating the records in 500 year time-slices, the chronological uncertainty is smoothed.

In order to assess the spatial robustness of the C-IT reconstructions we conducted a series of experiments on the interpolations. For each Lateglacial time-slice we removed a random set of 25% of the sites, and re-ran the analyses. We repeated this 500 times, and assessed the difference between the mean results from each run using the reduced dataset and the run using the full dataset. Because more sites are available in the early Holocene we removed randomly 33% of the sites to test the results of the early Holocene time-slices.

Full details of the locations of the beetle records appear in Coope *et al*. (1998) and the chironomid sites are shown in Fig 1. Coverage is fairly even across northwest Europe, although beetle records are lacking from northern Scotland, northern Scandinavia and eastern Europe. Chironomid records are lacking from southwest Britain. Details of the chironomid sites used in the analyses appear in Table 1.

Results and Discussion

The isotherm maps presented in this paper provide a striking visual depiction of summer air temperature development over the landmass of northwest Europe during the Lateglacial – early Holocene transition. In this discussion we will first highlight the major gradients and trends apparent in the C-IT data and discuss the likely mechanisms driving these temperature developments. Second, we will contrast and compare the C-IT against the B-MCR data and discuss likely reasons for any major differences between these data. Third, we will consider the reliability of the data we present and discuss the reasons for any major shortfalls. Finally, we will use the maps to identify gaps in the geographical and temporal coverage of our data in order to prioritise the locations for new summer temperature records.

Major gradients and trends

Coope and Lemdahl (1995) discuss the role of North Atlantic surface water, the Fennoscandian ice sheet and the ice free continent in influencing the spatial and temporal temperature changes across NW Europe during the Lateglacial. We see a strong north-to-south C-IT gradient is apparent in all the Lateglacial isotherm maps (Fig 3). This is most evident during the warm periods (GI-1e, GI-1c and GI-1a) when the isotherms generally trend N-S across the entire region. The strong influence of the Scandinavian ice sheet on continental European C-IT can be seen in the relatively steep gradient during these times, when the isotherm bands are narrower than those over the British Isles. The influence of the Scandinavian ice cap also has an influence on the rate of warming during GI-1. Peak C-IT are reached in the west and south of the region during GI-1e but warming in the north of the region is delayed until GI-1c or GI-1a as the ice sheet begins to recede. A west-to-east gradient in C-IT is also apparent due to the influence of the North Atlantic. This is particularly evident during the cool periods (GS-2, GI-1d and GS-1) when the isotherms strongly trend SE-NW over the British Isles but trend N-S over continental Europe. These trends and gradients emphasise the dominating influence of the status of the THC, especially during cool periods, in western parts of the region and how insolation, which rises through the Lateglacial – early Holocene transition, is dominant in driving temperature trends during warm periods, especially in the southern continental part of NW Europe. Also evident in the data are regional differences in the amplitude of cooling during GI-1. The southeast region is considerably warmer than northern and western regions, and the north-south thermal gradient is steeper in the east than in the west. Throughout the whole of northwest Europe, the coldest periods are GS-2 and GS-1. Temperatures drop throughout all regions during GI-1d, but remain a little warmer than during GS-2 or GS-1. The cooling during GI-1b is less severe. Following GS-1, warming trends in the early Holocene vary both spatially and temporally across all regions (Fig 4). High C-IT are apparent in the south and east earlier than in the west and north. This again emphasises the moderating local influences of the North Atlantic and the Scandinavian ice cap on C-IT. As the early Holocene progresses, the strong north-south gradient continues until c. 10 ka BP, when it weakens and an east-west gradient develops from 10-9 ka BP. During this time period the interior of the continent warms more rapidly than the coastal areas, although from 9-8.5 ka BP the gradient reduces. By 8 ka BP the coolest conditions are around the remains of the former Fennoscandian ice sheet, with Britain and continental Europe warming independently. Our analysis shows that during this period of the early Holocene maximum warmth is reached relatively early, around 10 ka BP.

Comparison between chironomid-inferred and beetle-inferred summer temperature estimates and trends

The major temperature gradients across NW Europe, together with the temporal and spatial shifts in these gradients, are similar in the isotherm maps generated from both proxies. However, there are some discrepancies.

Throughout much of the Lateglacial – Holocene transition, beetle-inferred temperatures (B-MCR) are about 2°C higher than chironomid-inferred temperatures (C-IT) (Fig 3). However, when the full range of B-MCR values, rather than just median values, are compared with C-IT values, including sample specific errors, many of the temperature estimates overlap. Nevertheless, this does not fully account for the consistency in the difference and suggests that there may be some bias in the estimates such that chironomids may be consistently underestimating temperatures and/or beetles may be consistently over-estimating values. Because the inference models based on each proxy have good performance statistics and accurately estimate modern temperatures this suggests that there may be some aspect of the Lateglacial climate boundary conditions, or some differences in the response of the proxies to non-analogue ecological conditions that is causing this consistent off-set.

This off-set, in which B-MCR estimates are higher than C-IT estimates, is particularly apparent during GI-1e (Fig 3). One possible explanation for this difference is the influence of microclimates on one or both of the proxies (Huntley, 2012). Early in the

Interstadial the ground was probably relatively open, having few trees, but there may have been significant snow beds present. Melting water from these snow beds may have caused lake water temperature to decouple from air temperature and fall below ambient air temperatures. There is evidence in the modern Norwegian dataset that lakes in these situations support chironomid assemblages typical of temperatures colder than expected from the local air temperature (Brooks and Birks, 2001). A chironomid assemblage in such a lake is therefore likely to produce a C-IT that underestimates air temperature. Conversely, solar insolation during the Interstadial was at its highest levels at the beginning of this period. In the absence of tree shade this is likely to have raised ground temperatures above those of air temperature at 1.5 m (the height that air temperature is measured in meteorological stations (Huntley, 2012)). A ground-dwelling beetle assemblage therefore may produce a B-MCR that overestimates air temperature.

There are some differences between the B-MCR and C-IT gradients across NW Europe during the Lateglacial – Holocene transition. During the GS-2 and GS-1 cold periods the C-IT records provide more detail of gradients because the B-MCR estimates (Coope *et al*., 1998) are not resolved below 9°C. During GI-1d, C-IT is depressed throughout the region. This is strongest over Britain and less strong in the southern part of the region. Although B-MCR estimates are also strongly depressed over Britain at this time, B-MCR inferred cooling is more subdued in continental Europe. Conversely, B-MCR estimates suggest that there was strong cooling across the region during GI-1b, but according to the C-IT estimates cooling was less strong during GI-1b and continental temperatures remained relatively high. The B-MCR trends during GI-1 reflect the trends in the NGRIP oxygen isotope ice core records (North Greenland Ice Core Project members, 2004) in which there is a strong decline in temperature throughout GI-1 and GI-1b reaches lower temperatures than GI-1d. The C-IT estimates, on the other hand, reflect oxygen isotope records from carbonate lake sites in NW Europe, such as Hawes Water (Marshall *et al*., 2002) and other sites in the English Lake District (Lang *et al*., 2010) and Ammersee in central Europe (von Graffenstein *et al*., 1999) in which cooling is stronger during GI-1d than GI-1b.

In Fig 5 we illustrate spatial and temporal differences in rates of temperature change during key periods in the Lateglacial and early Holocene. Our approach is to show the difference in temperature during certain key time slices compared to the start of the Holocene. Warmer temperatures on the resultant maps show that the time slice of interest was cooler than at 11 ka BP, whereas cooler temperatures indicate that the time slice was warmer than at 11 ka BP. The analysis clearly shows that western regions warmed much more rapidly during GI-1e, GI-1c and GI-1a than eastern regions (and northern regions for GI-1e), indicating the relative influence of warm currents from the THC and the cooling influence of the Scandinavian ice cap. The waning influence of the Scandinavian ice cap during GI-1 is also apparent. Conversely, during GS-1 cooling is stronger in regions bordering the North Atlantic than in the southeast of the region due to the influence of the shutdown of the THC and the expansion of the Scandinavian ice cap. By 8ka BP areas closest to the remains of the Scandinavian ice cap are the coldest in Europe whereas Iceland and western Europe are warmed by the THC.

Reliability of the data

There has been recent discussion (Velle *et al*., 2010; 2012; Brooks *et al*., 2012a) about the reliability of chironomids as temperature proxies. Variability in Holocene C-IT estimates between some Scandinavian sites, which are in relatively close proximity to one another, seems too large to be due to local differences in climate. This suggests that chironomid distribution and abundance may be less influenced by summer temperature than another variable, such as lake trophic status. Experimental work (e.g. Brodersen *et al*., 2008) has begun to reveal the response mechanisms of chironomid larvae to changing water temperature and oxygen, and carefully designed palaeoenvironmental studies (e.g. Stewart *et al*., 2013) are beginning to tease apart chironomid responses to the ecological interactions between temperature and lake productivity. This might compromise the validity of C-IT if lake trophic status varied independently of summer air temperature. However, despite the concerns of Velle *et al*. (2010), the C-IT isotherm maps do not indicate large local variability but instead C-IT estimates are spatially well-resolved (Figs 3 and 4). This suggests that during the Lateglacial – early Holocene transition summer temperature is the variable most influencing the distribution and abundance of chironomids. Since the data are presented in discrete time-slices and temperature bands, uncertainties in chronology and temperature are smoothed and produce a coherent and consistent picture of temperature development.

The tests we have undertaken suggest the C-IT we present in the isotherm maps are spatially robust (Fig 6). Removing a random 25% of data from the Lateglacial dataset resulted in most analyses agreeing with analyses based on the full dataset to within 1°C. The exception (not shown in Fig 6) was for the warm phases GI-1c and GI-1e, in which the C-IT around Hijkermeer and Zabieniec showed differences of up to 2°C between the reduced and full data set. This may be an artifact in the data reflecting the relatively low concentration of sites in these regions. The early Holocene isotherm maps also generally appear to be robust, as the majority of C-IT from the test analyses fall within 1°C of C-IT from the full dataset (Fig 6). However, later in the Holocene, the differences between the test data and the full dataset are larger. The test reveals that the least robust C-IT is from sites in southern Norway and Sweden, after 10 ka BP, and sites in western Scotland and Ireland at 8 ka BP. Velle *et al*. (2012) discuss regional discrepancies in C-IT from the Scandinavian sites, which seems to be the most problematic region across the whole NW European dataset, perhaps due to the relatively high topographic relief in this part of NW Europe.

The isotherm maps are plotted to reflect the style used in Coope *et al*. (1998) to simplify the comparison between the two datasets. Although the isotherms extend across the sea we should not expect the land-based temperature estimates to be the same as sea surface temperatures. There is a strong argument (Juggins 2013) that the chironomid modern calibration set is not designed to model sea surface temperatures. Nonetheless, it would be interesting to compare temperature inferences between terrestrial and marine based proxies across regions such as the North Atlantic and NW Europe in future studies.

Gaps in data

The isotherm maps provide a clear picture of temperature development in northwest Europe during the Lateglacial – Holocene transition but also serve to highlight gaps in the data. Most obvious is the need for more data points to provide an even coverage and denser network of sites. This would help to confirm the trends across the region or determine whether adding sites produces more noise and greater uncertainty in spatial resolution of temperature trends throughout the region. Additionally, data from more sites would provide local detail, showing the influence of mountain ranges on local temperatures, for example. Priority locations for new sites covering the Lateglacial – Holocene transition are northwest Scotland, southwest England and Wales, northeast France, Denmark, Finland and the Baltic States as currently there are no chironomid records from these areas.

Conclusions

Our new analyses of Lateglacial – Holocene transition chironomid-inferred temperature sequences from northwest Europe using isotherm maps clearly demonstrate that C-IT complement beetle-inferred MCR temperature data previously published in this form by Coope *et al*. (1998). Both data sets illustrate generally similar trends and gradients throughout most of the region and period, although discrepancies may reflect differences in the methodological approaches and underline the need for multiproxy records to validate results. Chironomids appear to produce spatially and temporally coherent temperature estimates, which suggest that they are reliable and that summer temperature has more influence on chironomid distribution and abundance than other environmental variables.

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Figure and table captions

Fig. 1. The location of the 22 Lateglacial and 34 early Holocene sites used in constructing the chironomid-inferred isotherm maps. Note that four sites (Little Hawes Water, Urswick Tarn, Cunswick Tarn and Sunbiggin Tarn), which are located close to Hawes Water, are not shown on this map.

Fig. 2. Absolute mean differences between kriging and IDW interpolation techniques for each of the seven Lateglacial time-slices comparing all sites and all sites excluding Jansvatnet.

Fig. 3. Lateglacial isotherm maps. Main map based on chironomid-inferred summer air temperature estimates using the Norwegian temperature calibration dataset. Coleoptera-inferred MCR temperature of the warmest month estimates are shown inset at top left.

Fig. 4. Holocene isotherm maps based on chironomid-inferred summer air temperature estimates using Icelandic (Langdon *et al*., 2008), Norwegian (Brooks and Birks 2000; 2001; 2004; unpublished), Swedish (Larocque *et al*., 2001) or Finnish (Olander *et al*., 1999) temperature calibration datasets. The time windows are calibrated dates.

Fig. 5. Isotherm maps showing differences in chironomid-inferred temperature estimates between early Holocene and selected time-slices in the Lateglacial Interstadial and early Holocene.

Fig. 6. Holocene summer air temperature isotherm maps testing the robustness of the chironomid-inferred isotherms. A third of the sites were removed from a test set of data, and the test set was used for spatial interpolation using kriging techniques. This was repeated 500 times, and the mean differences between the test sets and full dataset are shown on these maps.

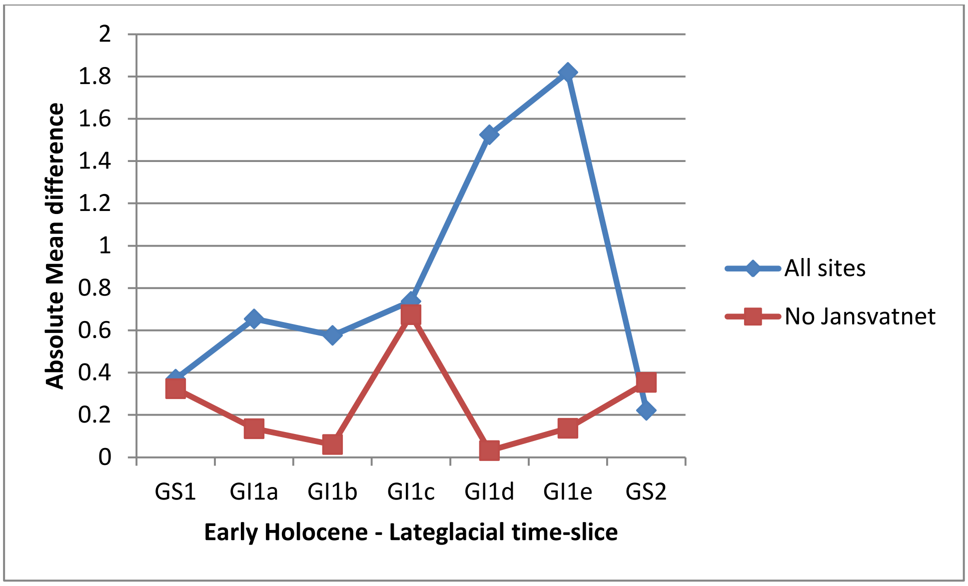
Table 1. Sites used in analysis

711

Figure 1


Late Glacial Sites
Holocene Sites
Jansvatnet
Toskalijavri
Lusvatnet
Bjornfjelltjørn
Njulla
Tsuolbmajavri
Vuoskkujavri
Lake 850
Seukokjaure
Sjuodjijaure
Berkut
Efstadalsvatn
Hámundarstaðaháls
Vatnamýri
Spåime
Dovre Mountains
Ratasjoen
Kråkenes
Brurskardstjørni
Hirvijarvi
Myklevatnet
Finse Stasjonsdam
Vestre Øykjamyrtjørn
Gilltjärnen
Holebudalen
Loch Ashik
Abernethy
Bjerkreim
Lochnagar
Loch an t'Suidhe
Hässeldala port
Whitrig Bog
Lough Nadourcan
Hawes Water
Friedlander Grosse Wiesse
Fiddaun
Hijkermeer
Quidenham Mere
Zabieniec
Klein Ven
0
200
400 Miles

Figure 2



Absolute Mean difference
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
GS1
GI1a
GI1b
GI1c
GI1d
GI1e
GS2
Early Holocene - Lateglacial time-slice
All sites
No Jansvatnet

Figure 3

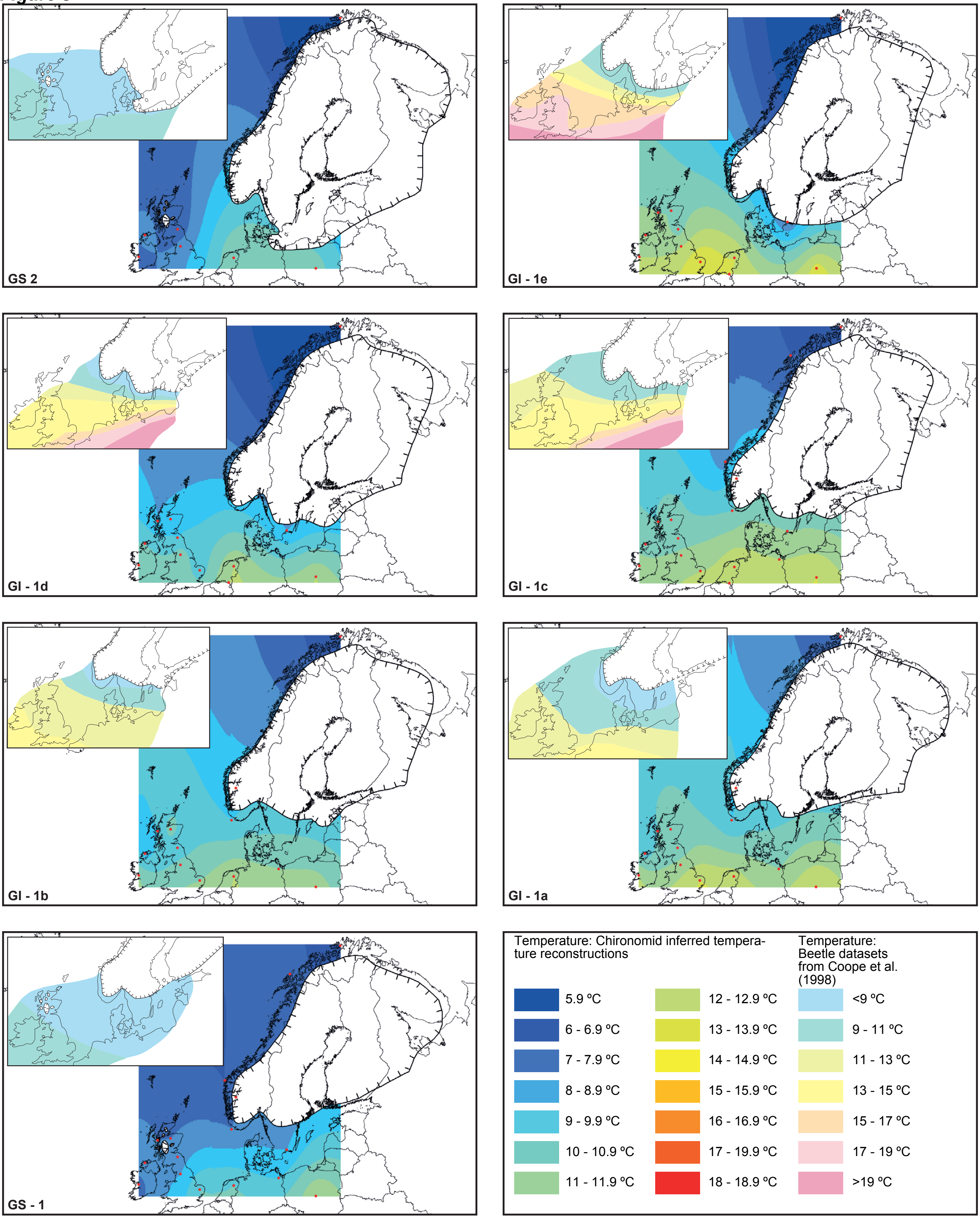

GS 2
GI - 1e
GI - 1d
GI - 1c
GI - 1b
GI - 1a
GS - 1
Temperature: Chironomid inferred temperature reconstructions
5.9 ºC
6 - 6.9 ºC
7 - 7.9 ºC
8 - 8.9 ºC
9 - 9.9 ºC
10 - 10.9 ºC
11 - 11.9 ºC
12 - 12.9 ºC
13 - 13.9 ºC
14 - 14.9 ºC
15 - 15.9 ºC
16 - 16.9 ºC
17 - 19.9 ºC
18 - 18.9 ºC
Temperature: Beetle datasets from Coope et al. (1998)
<9 ºC
9 - 11 ºC
11 - 13 ºC
13 - 15 ºC
15 - 17 ºC
17 - 19 ºC
>19 ºC

Figure 4

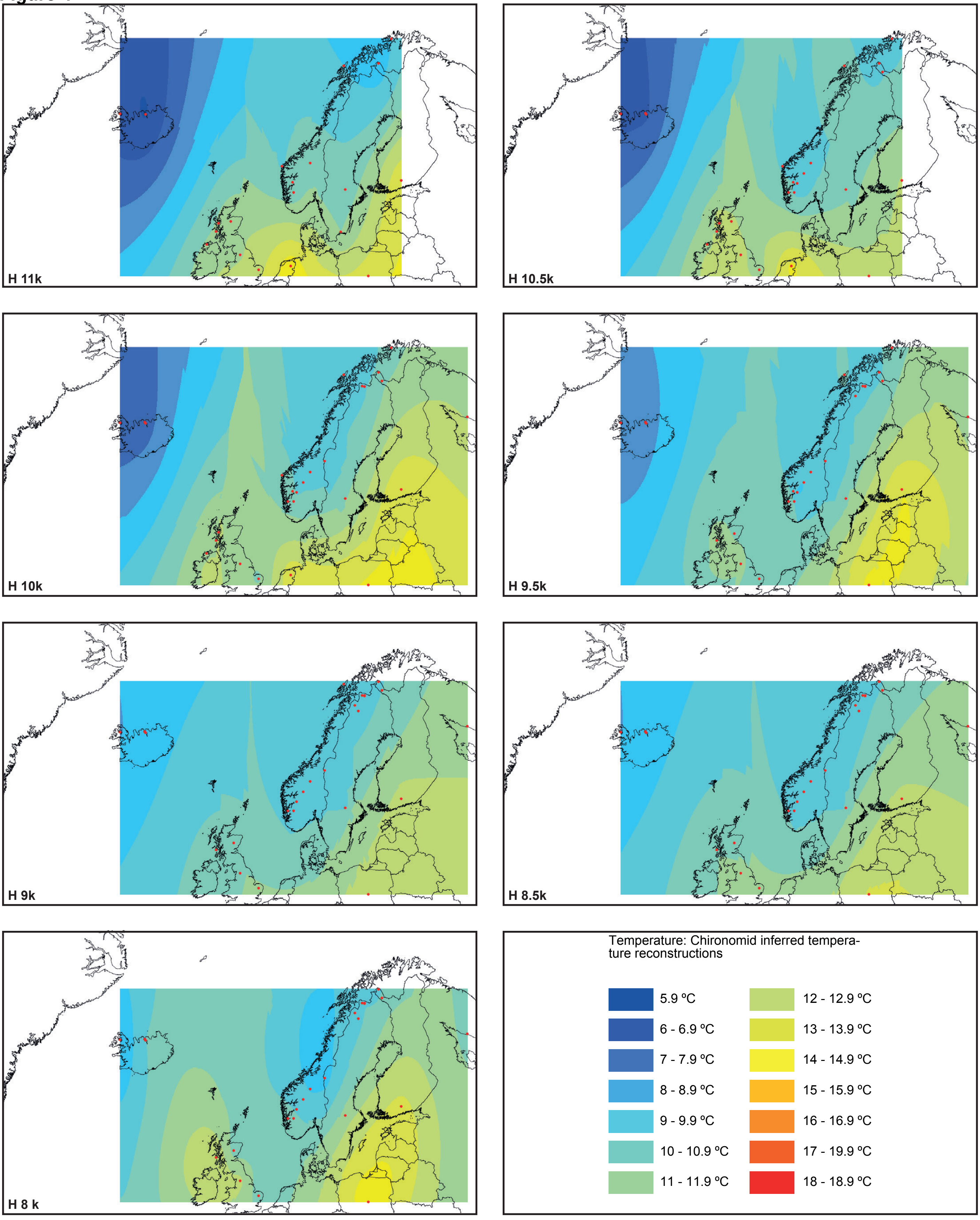
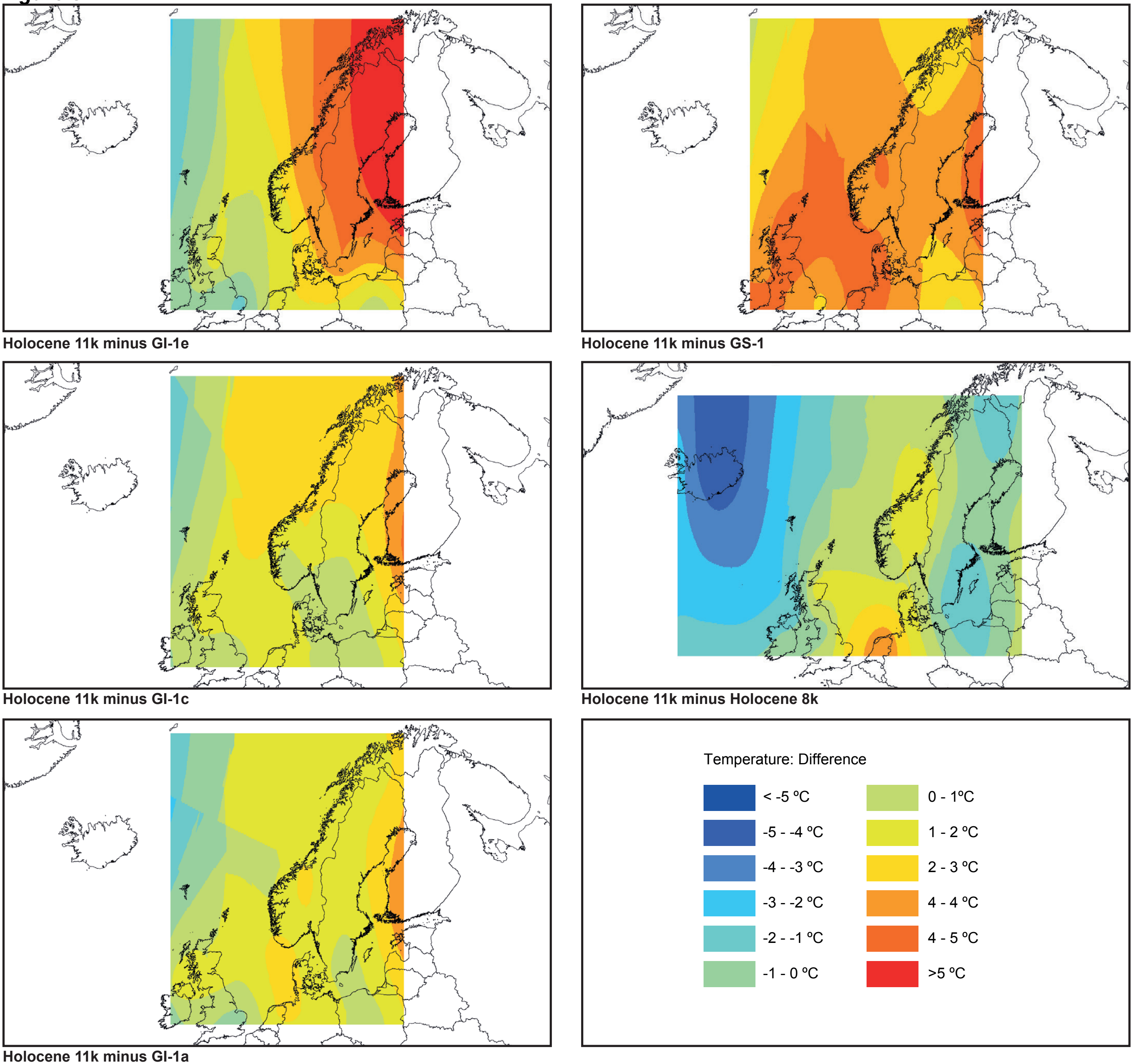

H 11k
H 10.5k
H 10k
H 9.5k
H 9k
H 8.5k
H 8 k
Temperature: Chironomid inferred temperature reconstructions
5.9 ºC
6 - 6.9 ºC
7 - 7.9 ºC
8 - 8.9 ºC
9 - 9.9 ºC
10 - 10.9 ºC
11 - 11.9 ºC
12 - 12.9 ºC
13 - 13.9 ºC
14 - 14.9 ºC
15 - 15.9 ºC
16 - 16.9 ºC
17 - 19.9 ºC
18 - 18.9 ºC

Figure 5



Holocene 11k minus GI-1e
Holocene 11k minus GS-1
Holocene 11k minus GI-1c
Holocene 11k minus Holocene 8k
Holocene 11k minus GI-1a
Temperature: Difference
< -5 ºC
-5 - -4 ºC
-4 - -3 ºC
-3 - -2 ºC
-2 - -1 ºC
-1 - 0 ºC
0 - 1ºC
1 - 2 ºC
2 - 3 ºC
4 - 4 ºC
4 - 5 ºC
>5 ºC

Figure 6

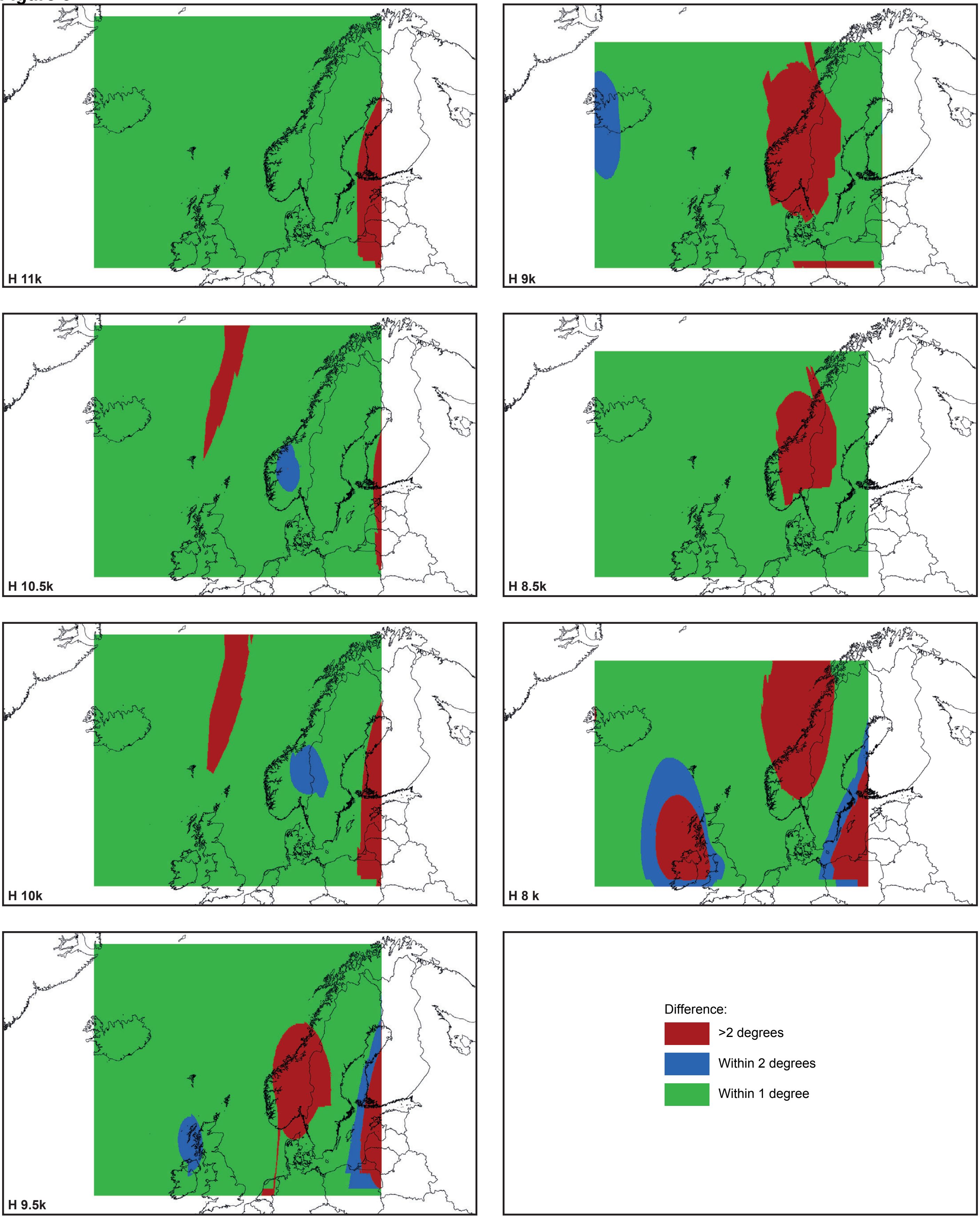

H 11k
H 9k
H 10.5k
H 8.5k
H 10k
H 8 k
H 9.5k
Difference:
>2 degrees
Within 2 degrees
Within 1 degree

Table 1. Sites used in analysis

Country	**Site name**	**Latitude**	**Longitude**	**Altitude (m asl)**	**Source**
Iceland	Efstadalsvatn	66°55’N	21°40’W	123	Caseldine *et al.* (2003)
Iceland	Vatnamýri	65°54’N	18°18’W	220	Caseldine *et al.* (2006)
Iceland	Hámundarstaðaháls	65°58’N	18°27’W	100	Caseldine *et al.* (2006)
Ireland	Fiddaun	53°00’N	08°52’W	30	van Asch *et al.* (2012c)
UK, N. Ireland	Lough Nadourcan	55°03’N	07°54’W	70	Watson *et al.* (2010)
UK, Scotland	Loch Ashik	57°05’N	05°50’W	145	Brooks *et al.* (2012b)
UK, Scotland	Abernethy	57°15’N	03°43’W	340	Brooks *et al.* (2012b)
UK, Scotland	Lochnagar	56°58’N	03°14’W	650	Dalton *et al.* (2005)
UK, Scotland	Loch an t’Suidhe	56°18’N	06°14’W	85	Edwards *et al.* (2007)
UK, Scotland	Whitrig Bog	55°36’N	02°36’W	125	Brooks and Birks (2000)
UK, England	Hawes Water	54°11’N	02°48’W	8	Lang *et al.* (2010)
UK, England	Little Hawes Water	54°11’N	02°47W	9	Lang *et al.* (2010)
UK, England	Sunbiggin Tarn	54°27’N	02°30’W	250	Lang *et al.* (2010)
UK, England	Cunswick Tarn	54°20’N	02°47’W	135	Lang *et al.* (2010)
UK, England	Urswick Tarn	54°09’N	03°70’W	33	Lang *et al.* (2010)
UK, England	Quidenham Mere	52°30’N	01°00’E	30	Jeffers *et al.* (2011)
Norway	Jansvatnet	70°39’N	23°40’E	53	Birks *et al.* (2012)
Norway	Bjornfjelltjørn	68°26’N	18°04’E	510	Brooks (2003)
Norway	Lusvatnet	69°04’N	15°34’E	36	Brooks (unpublished)
Norway	Dovre Mountains	62°28’N	09°37E	1260	Paus *et al*. (2011)
Norway	Ratasjoen	62°16’N	09°50’E	1169	Velle *et al.* (2005)
Norway	Kråkenes	62°00’N	05°00’E	40	Brooks and Birks (2001)

Norway	Brurskardstjørni	61°25’N	08°40’E	1309	Velle *et al.* (2005)
Norway	Myklevatnet	60°42’N	06°50’E	580	Nesje *et al.* (submitted)
Norway	Finse Stasjonsdam	60°36’N	07°30’E	1208	Velle *et al.* (2005)
Norway	Vestre Øykjamyrtjørn	59°49’N	06°00’E	594	Velle *et al.* (2005)
Norway	Holebudalen	59°50’N	06°59’E	1144	Velle *et al.* (2005)
Norway	Bjerkreim	58°36’N	06°07’E	129	Brooks (unpublished)
Finland	Toskalijavri	69°12’N	21°28’E	704	Seppä *et al.* (2002)
Finland	Tsuolbmajavri	68°14'N	22°10'E	526	Korhola *et al.* (2002)
Finland	Hirvijarvi	60°51’N	25°23’E	104	Luoto *et al.* (2010)
Sweden	Njulla	68°22'N	18°42'E	999	Larocque and Hall (2004)
Sweden	Vuoskkujavri	68°20'N	19°06'E	348	Larocque and Hall (2004)
Sweden	Lake 850	68°15'N	19°07'E	850	Larocque and Hall (2004)
Sweden	Seukokjaure	67°46'N	17°31'E	670	Rosén *et al.* (2003)
Sweden	Sjuodjijaure	67°22'N	18°04'E	826	Rosén *et al.* (2001)
Sweden	Spåime	63°07’N	12°19’E	887	Hammarlund *et al.* (2004)
Sweden	Gilltjärnen	60°04’N	15°50’E	172	Antonsson *et al.* (2006)
Sweden	Hässeldala port	56°16’N	15°03E	63	Watson (unpublished)
The Netherlands	Hijkermeer	52°53’N	06°29’E	14	Heiri *et al.* (2007)
The Netherlands	Klein Ven	51°17’N	05°39’E	36	van Asch *et al.* (2012a)
Germany	Friedlander Grosse Wiesse	53°38’N	13°45’E	10	van Asch *et al.* (2012b)
Poland	Zabieniec	51°51’N	19°46’E	180	Plociennik *et al.* (2011)
Russia	Berkut	66°20’N	36°39’E	25	Ilyashuk *et al.* (2005)

***Detailed Response to Reviewers**

Reviewer #1: Very interesting paper. Enjoyed reading it, fascinating results that will open up discussion and new work. *Thanks for your positive comments*

Some other comments:
Lines 191-209 - this sections discusses that Jansvatnet is an outlier. Would be interesting to know what sort of outlier analysis has taken place?
We have changed this sentence as follows:
The sites for these time slices are generally clustered relatively close together, however, Jansvatnet, in the extreme north of Scandinavia, was ~~an outlier~~ remote from other sites and this is the most likely reason for the different results between the two interpolation techniques.

Lines 67-92 - there have been published updates to the MCR method taking account of ubiquity.
We have added a reference to ubiquity analysis (Bray et al 2006 QSR) in line 82.

Lines 351-365 - Good discussion - would it be worth mentioning that we can use tools and application from ecology to determine if species distributions are more dependent on some variables than others? *We have added discussion of two studies as examples that have used ecological approaches to determine how chironomids respond to temperature and other environmental variables (lines 368-372).*

Figs - How do you interpret the temperature reconstructions in areas where there is very little data (eg North cost of Scandinavia)?
Caution is required in areas where sites are far apart and we cover this in the discussion especially under the section on gaps in the data.

What about the fact that these isotherms also make an inference on ocean temperature? Can we trust chironomid data to do this? How do these ocean temperatures compare with ocean-based proxies? I think some LG/Holocene reconstructions have been done with molluscs.
We should not expect the land-based temperature estimates to be the same as SST. A comparison could be made of anomalies compared with modern temperatures (see also Simonis et al (2012) Quat Int) but it would be outside the scope of this paper to start comparing anomalies and SST with the C-IT and MCR temperature estimates. There is a strong argument (Juggins 2013) that the chironomid modern calibration set is not designed to model SST. The isotherm maps are plotted to reflect the style used in Coope et al (1998) to simplify the comparison between the two datasets. A discussion of this point has been added (lines 398-402).

Reviewer #2: General comments:
This is an important contribution which presents summer air temperatures isotherm maps based on chironomid inferred reconstructions, similar to what was presented fifteen years ago based on beetle data by using the MCR method. The data set and the method using chironomids for temperature reconstructions, statistics applied and possible factors that influence accuracy of the data sets and the reconstructions are thoroughly described. Most valuable is the comparison between the isotherm maps based on beetle data and those based on the chironomid data. Relevant conclusions are drawn concerning both similarities and differences in the results from the two types of proxy data. Reasons for the differences shown in the paper are proposed in the discussion, which obviously generate a future debate. The article is very well written, I find not much to add or to remove. All the figures are relevant and of high quality. *Thanks for your positive comments*.

Additional comments:

* I think it would be helpful for the readers to know what time periods are covered by each of the seven Lateglacial time slices. This would preferably be added in the figures or in a table. The chronology of the time slices is expressed in "ka BP", as in Coope et al. (1998), which are uncalibrated radiocarbon years. However, the first time slice in Holocene series is dated to 11 ka, the next to 10.5 etc. These are calibrated dates! Consequently, there seems to be a mixture of calibrated and uncalibrated ages in the article which is problematic and confusing. I suggest that same type of chronology should be used for all the presented time slices, preferably expressed in calendar years.

We have added to the text the time periods covered by each of the seven Lateglacial time slices (lines 218-220). We do not refer to the uncalibrated dates used by Coope et al, but rather allocate the Coope time slices to the appropriate one of the seven Lateglacial time slices in Fig. 3. All dates used in our paper are calibrated dates.

* In Figure the C-IT data is adjusted for altitude. It is not clear to me how this was carried out. As the isostatic uplift has been a non-linear process since the areas were deglaciated you need a model for each area in order to calculate the accurate altitude for each site at each time. Moreover, the isostatic uplift has been and is presently unique in different areas depending on the thickness of the previous ice cover and the time for the deglaciation. Logical, you should also consider the eustatic changes in sea level too, as altitudes are referred to above contemporary sea level. Consequently, if you have just used modern values for the adjustment this is not relevant for the Lateglacial and the early Holocene. *We have deleted this figure.*

Specific remarks

Page 2, Line 73-75: "Beetle remains. larger quantities of sediment, typical obtained from sections dug from old lake beds or river channels, are required for analysis." Well that may be true for most of the British sites in Coope et al. (1998), but not for the sites in e.g. Scandinavia, Finland and Poland included in Coope et al. (1998). Normally, similar sample volumes used for plant macrofossil analysis that are obtained by coring are required.

We have changed this sentence to reflect this.

P. 2, L. 90-92: Correct, fifteen years ago we used median calibrated values calculated by using a regression equation. That method we have abandoned. See Bray et al. (2006) and Buckland (2007).
We have added the following sentence (lines 80-84): The method for estimating temperatures has subsequently been refined to make MCR estimates more reliable by including ubiquity analysis (Bray et al 2006) to provide a better model of climate space occupied by a species, and jackknifing techniques to provide an estimate of the standard error of the MCR (Buckland 2007).

P. 4, L. 182-184: Temperatures "significant" for an entire time slice are given for each site. They were in most cases an average from a series of MCR estimates, without applying statistical tools. This is obviously a weakness of the presented MCR isotherm maps and that we would have done differently today. However, the objective of the study was more to illustrate a changing pattern of temperature gradients, which had earlier been presented as "regional differences in climate development" in Coope and Lemdahl (1995).
We thank the reviewer for this information and have changed this section to reflect this (lines 185-189)

P. 5, L. 205-206, and P. 9, L. 383-396: No high altitude sites are included in Coope et al. (1998). Consequently, a correction for altitude would not change the MCR estimates much. In the contrary,

the C-IT records are obtained from sites situated between 8 to 1260 m a.s.l. An adjustment here would be more appropriate. Unfortunately, this is not a simple task as you have to consider non-linear isostatic land uplift. See further under "Additional comments".
In view of this valuable point concerning isostatic uplift we have decided to delete Figure 7 and the text referring to this.

P. 6, L. 252-260: It may be appropriate to mention Coope and Lemdahl (1995) which suggested that the larger regional differences during interstadials and hardly no differences during [stadials], may be ascribed the varying influence of North Atlantic surface water temperatures, the proximity of the Fennoscandian ice sheet, and the ice free continent.

We have added the following sentence at the beginning of the section starting on line 258: Coope and Lemdahl (1995) discuss the role of North Atlantic surface water, the Fennoscandian ice sheet and the ice free continent in influencing the spatial and temporal temperature changes across NW Europe during the late glacial. We see a strong …….

References: Hammarlund et al. (2004) is cited in the text but is not in the reference list.
Hammarlund, D, Velle, G, Wolfe, BB, Edwards TWD, Barnekow L, Bergman J, Holmgren S, Lamme S, Snowball I, Wohlfarth B, Posnert g. 2004 Palaeolimnological and sedimentary responses to Holocene forest retreat in the Scandes Mountains, west-central Sweden. The Holocene 14: 862-876.

This reference has been added

There are two Brooks et al. 2012 in the reference list that ought to be separated as 2012a and 2012b when cited. *This has been corrected.*
I cannot find the citation of "North Greenland Ice Core Project members (2004)" in the text. Please check that. *Cited in line 223.*

Figure 1 and Table 1: Please check the spelling of sites in Scandinavia and Finland. *Figure 1 has been corrected.*

Quoted References:

Bray PJ, Blockey SPE, Coope GR, Dadswell LF, Elias SA, Lowe JJ, Pollard 2006. Refining mutual climatic range (MCR) quantitative estimates of palaeotemperature using ubiquity analysis. Quaternary Science Reviews 25, 1865-1876.

Buckland PI 2007. The development and implementation of software for palaeoenvironmental and palaeoclimatological research: The Bugs Coleopteran Ecology Package (BugsCEP). Archaeology and Environment 23, Umeå University, Department of Archaeology and Sámi Studies, 220 pp.

Coope GR, Lemdahl G 1995. Regional differences in the Lateglacial climate of northern Europe based on coleopteran analysis. Journal of Quaternary Science 10, 391-395.

These references have been added.