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A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps

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Abstract: We developed a quantitative chironomid-July air temperature inference model based on surface sediments from 81 Swiss lakes and applied it to the Holocene subfossil chironomid record of Hinterburgsee, a small subalpine lake in the northern Swiss Alps (present-day mean July air temperature of 11.3°C). After smoothing to reduce the high between-sample variability of inferred temperatures, the reconstruction indicates July air temperatures of 10.4–10.9°C at the end of the Younger Dryas, of 11.9–12.8°C during the early and mid-Holocene (11500–4000 cal. BP), and slightly lower temperatures of 11.5–12.0°C during the late Holocene (3500–1000 cal. BP). A warming trend inferred for the past millennium is most likely an artifact of human impact on Hinterburgsee's chironomid fauna, rather than a genuine temperature signal. The most prominent climatological events during the Holocene were two periods of lower temperatures at *c.* 10700–10500 cal. BP and 8200–7700 cal. BP and an abrupt shift to a cooler late-Holocene climate around 4000–3700 cal. BP. Although the chironomid-inferred climate signals were within the prediction error of the model (1.51°C), major inferred temperature changes agree well with other northern and central European climate reconstructions and underline the potential of subfossil chironomid analysis to reconstruct even the moderate climatic changes within the Holocene.

Key words: Climatic reconstruction, subalpine lake, Holocene climate, July air temperature, chironomids, organism-based inference models, Swiss Alps.

Introduction

Palaeotemperature reconstructions provide an important basis for understanding the dynamics and functioning of the climatic system. Observed recent temperature trends must be assessed in relation to the natural, long-term dynamics of the climatic system (Bradley, 2000). Furthermore, accurate temperature reconstructions are necessary to evaluate climate models that enhance our understanding of global climate dynamics and are ultimately used to predict future climate under changed boundary conditions (e.g., COHMAP Members, 1988; Renssen and Isarin, 1998). Instrumental temperature records are generally only available from the last 100 to 150 years. Temperature proxies, e.g., isotope records from ice cores or lake sediments, tree-ring sequences or fossil remains of organisms in sediments, provide an alternative means of reconstructing past temperatures (e.g. Schweingruber *et al.*, 1991; GRIP members, 1993; von Grafenstein *et al.*, 1998; Lotter *et al.*, 2000). Many of these records provide continental temperature estimates covering a large part of the Holocene, some even reaching back to the Lateglacial period.

In the Alps, a number of palaeobotanical studies have provided evidence of past temperature fluctuations (e.g., Patzelt, 1977; Bircher, 1986; Lang, 1993). Since the upper limit of tree-growth in mountain regions is closely related to temperatures during the growing season (Tranquillini, 1979; Dahl, 1986), one of the most convincing approaches to infer past Alpine summer temperatures is to reconstruct former treeline elevations (e.g., Patzelt, 1977; Burga and Perret, 1998). Using plant macrofossil and pollen records from lakes at present-day treeline, Wick and Tinner (1997) described a number of partly synchronous treeline oscillations from the central and southern Alps that agree with other temperature reconstructions in the Alpine region (Haas *et al.*,

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1998). However, reconstructing past treelines based on pollen analysis is difficult due to the bias of long-distance pollen transport (Lang, 1993). If past treeline fluctuations are to be used to provide quantitative estimates of past summer temperatures, plant macrofossils (or fossil stomata; Ammann and Wick, 1993) need to be analysed in a number of lakes across an altitudinal gradient in order to constrain former treeline altitudes.

Alternatively, organism-based inference models can be used to provide a direct estimate of past temperatures from fossil assemblages (Birks, 1995; Lotter *et al.*, 1997). Subfossil remains of chironomid larvae (Insecta: Diptera: Chironomidae) from lake sediments have proven to be particularly useful temperature indicators (Walker *et al.*, 1991b; Battarbee, 2000). Along a large climatic gradient summer temperature is commonly the environmental factor explaining the most variance in subfossil chironomid assemblages (e.g., Walker *et al.*, 1991b; Lotter *et al.*, 1997). Thus, a number of chironomid-summer temperature inference models have been developed and successfully used to reconstruct the major climatic fluctuations of the Lateglacial (e.g. Walker *et al.*, 1991a; Levesque *et al.*, 1993; Brooks and Birks, 2000a; 2000b). However, only few chironomid-based reconstructions are available for the Holocene (e.g., Smith *et al.*, 1998; Pellatt *et al.*, 2000; Rosén *et al.*, 2001). This may be because the prediction errors of the models (expressed as root mean square error of prediction; RMSEP) are generally of the same magnitude or larger than the expected Holocene temperature changes. Furthermore, during the Holocene factors such as vegetation changes, lake infilling and early human impact (e.g., catchment clearcutting and pasturing) may have a stronger influence on the lakes than temperature (e.g., Renberg *et al.*, 1993; Korsman *et al.*, 1994; Francis, 2001) and may therefore cause a bias in chironomid-inferred temperature reconstructions.

In this study, we present an extended chironomid-July air temperature inference model that is used to reconstruct Holocene temperatures at Hinterburgsee, a small lake in the subalpine belt of the Bernese Alps, Switzerland. Chironomid assemblages at this altitude in the northern Swiss Alps seem to be particularly sensitive to changes in summer air temperature (Lotter *et al.*, 1997). Furthermore, as these subalpine lakes commonly feature high sedimentation rates, they can produce environmental reconstructions of a high temporal resolution.

Site and methods

Hinterburgsee (46°43′07″N, 8°04′07″E) is a small lake in the subalpine vegetation zone at 1515 m a.s.l. in the Bernese Alps, Switzerland (Figure 1). It is located above the southern shore of Lake Brienz, *c.* 16 km east of Interlaken and 4.5 km south to southwest of Brienz, and features a present-day mean July air temperature of 11.3°C. In summer 1998, a sediment core reaching back into the Lateglacial period was recovered from the deepest part of the lake (see Heiri *et al.*, 2003, for details on the site, subfossil chironomid record and age-depth modelling). Sixteen samples of terrestrial plant remains from the sediment were dated using accelerator mass spectrometer (AMS) radiocarbon dating. Together with a palynological date (Younger Dryas/Holocene boundary) they provided the basis of an age-depth model reaching back to *c.* 11500 calibrated radiocarbon years BP (cal. BP). The age-depth modelling (Figure 2) is based on non-parametric weighted regression within the framework of Generalized Additive Models (Hastie and Tibshirani, 1990) and on radiocarbon dates calibrated using the CALIB 4.1.2. program (Stuiver and Reimer, 1993). Lateglacial ages were estimated by linear extrapolation beyond the Holocene/Younger Dryas boundary. A total of 62 sediment samples were analysed for subfossil chironomids (Figure 3; Heiri *et al.*, 2003). Depending on the sediment depth, a single sample encompassed between 10 and 50 years of sedimentation and the chironomid record has a resolution of about one sample every 100–300 years.

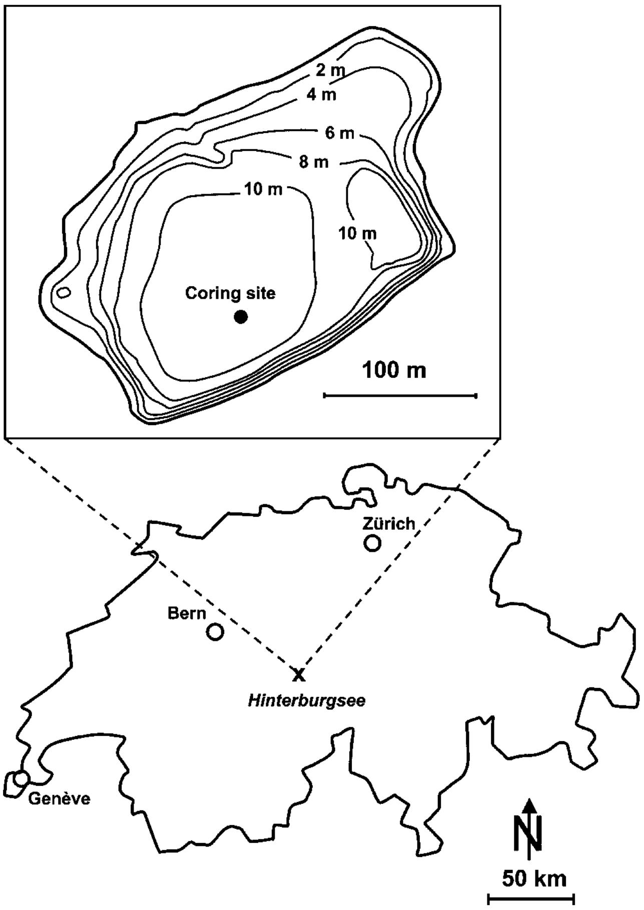

Figure 1 Contour map of Switzerland showing the location of Hinterburgsee. The inset map shows the lake bathymetry (following Spengler, 1973, changed) and the coring site within the lake basin.

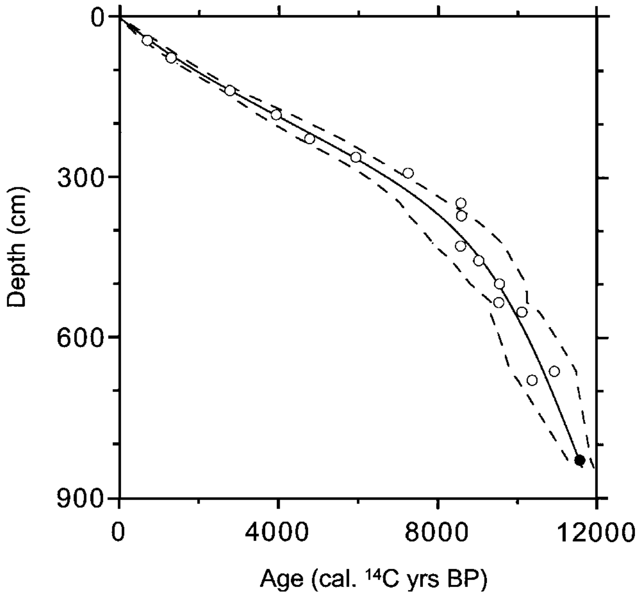

Figure 2 Dating of the Hinterburgsee sediment core: age-depth model (solid line) and 95% confidence intervals (dashed lines). Open circles indicate the calibrated radiocarbon dates used for the model; the closed circle indicates a pollen-inferred age.

A chironomid-July air temperature inference model was developed using surface-sediment samples obtained from 89 small

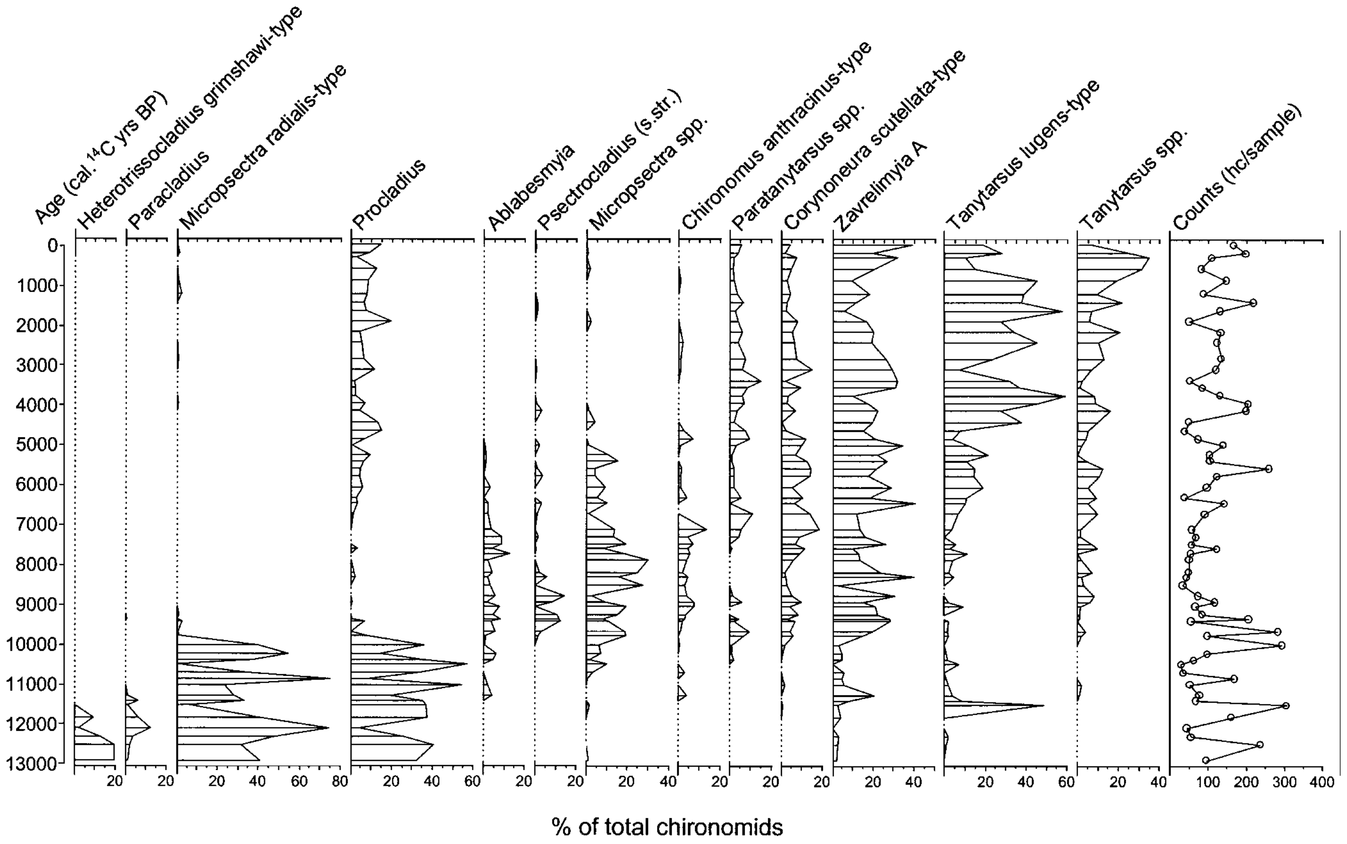

Figure 3 Summary diagram of the most common chironomid taxa recovered from the Hinterburgsee sediments (see Heiri *et al.*, 2003, for a detailed description of the subfossil chironomid record). Abundances for the individual taxa are given as percentages and the counts as head capsules (hc) per sample.

Swiss lakes (following the methodology described in Lotter *et al.*, 1997). Results of 50 of these lakes have been previously published (Lotter *et al.*, 1997). However, for the present study all the original slides have been re-examined to increase the taxonomic resolution and to harmonize the taxonomy with the downcore record. GIS-based mean July air temperature was estimated for each lake following Lotter *et al.* (1997). Further information on the lakes is given in Lotter *et al.* (1997; 1998); Müller *et al.* (1998) and Heiri (2001).

The chironomid-July air temperature inference model was developed using the program CALIBRATE (S. Juggins and C.J.F. ter Braak, unpublished software) and sample specific error estimates were calculated by 999 bootstrap cycles using the program WAPLS (S. Juggins and C.J.F. ter Braak, unpublished software). Analogue and goodness-of-fit statistics were calculated following Birks *et al.* (1990), Birks (1995), Jones and Juggins (1995) and Birks (1998). A cut-level of the 5th and the 10th percentile in the modern residual chi-square distances was chosen for samples with a 'very poor' and a 'poor' fit to temperature and a cut level of the 2nd and 5th percentile of all chi-square distances within the modern data for samples with no 'close' and no 'good' analogues, respectively. Furthermore, we calculated the percentage of rare taxa for each fossil sample, where rare taxa are defined as having a Hill's N_2 (Hill, 1973) of 5 or less in the modern chironomid data. Canonical Correspondence Analysis (CCA) and Detrended Canonical Correspondence Analysis (DCCA) were accomplished using CANOCO version 4.0 (ter Braak and Smilauer, 1998) and analogues calculated using MAT (S. Juggins, unpublished software). Smoothing of the inferred July air temperatures was achieved by fitting a LOESS model (Cleveland and Devlin, 1988) with a gaussian error distribution, a locally linear fitting and a span of 0.1 to the data points using the program SPLUS 4.5 (MathSoft, Inc.). For all calculations the chironomid percentage data were square-root transformed.

Results

July air temperature inference model

Chironomid data and July air temperatures of 89 lakes from the Jura Mountains, the northern Swiss lowland and the northern and central Swiss Alps were available for regression of the chironomid-July air temperature inference model. In order to reduce noise in the chironomid data due to low counts, the minimum count level was set to 45 (Heiri and Lotter, 2001), leading to the exclusion of four lakes from the analysis. One sample was eliminated from the regression as it was dominated by a single taxon absent in the subfossil chironomid record of Hinterburgsee and otherwise rare in Swiss lakes. Three further lakes were eliminated as they are used as regulating basins for hydropower generation or subject to occasional flooding by a nearby river. In the remaining samples, taxa with fewer than three occurrences were deleted. The final data set contained 76 chironomid taxa and 81 samples spanning an altitudinal range from 420 to 2490 m a.s.l. and featuring observed mean July air temperatures from 6.9 to 18.4°C. In a Detrended Canonical Correspondence Analysis (DCCA) with July air temperature as the only constraining variable the first axis featured a gradient length of 2.7 standard deviation units, indicating that unimodal-based regression techniques are appropriate (Birks, 1995). Furthermore, the analysis revealed a significant secondary gradient in the chironomid data (length of DCA axis 2 of 3.1 standard deviations, significance assessed following Birks, 1998). In a Canonical Correspondence Analysis (CCA), July air temperature explained 13.1% of the variance in the chironomid data and was highly significant ($P < 0.0001$) when tested by a Monte Carlo permutation test (9999 unrestricted permutations; ter Braak, 1990; 1992; Birks, 1998).

Weighted averaging-partial least squares regression (WAPLS; ter Braak and Juggins, 1993; ter Braak *et al.*, 1993) with two components yielded a chironomid-July air temperature inference model with a coefficient of determination (r^2) of 0.81 and a root mean square error of prediction (RMSEP) of 1.51°C as assessed by leave-one-out cross-validation (Figure 4). As expected in a data set with a strong secondary gradient (Birks, 1998), it outperformed weighted averaging (WA) with classical deshrinking (r^2 = 0.74, RMSEP = 1.96°C), WA with inverse deshrinking (r^2 = 0.74, RMSEP = 1.77°C) and WA methods with tolerance downweighting (r^2 = 0.60–0.64, RMSEP = 2.23–2.40°C; see Birks, 1995, for details on these WA-based methods). WAPLS with three components provided only slightly better model statistics (r^2 = 0.82, RMSEP = 1.47°C) and the simpler two-component model was therefore retained. The two-component WAPLS model has a tendency to infer too high temperatures at the cold end of the temperature gradient (Figure 4), but these edge effects do not influence temperatures close to the present-day July air temperature of 11.3°C at Hinterburgsee. Finally, the model was tested for statistical outliers following the approach of Lotter *et al.* (1997), but, as no sample combined the attributes of a high absolute residual and a low Cook's D or a high absolute residual, a high Cook's D and a very high residual chi-square distance in a CCA, no further lakes were excluded from the model.

Temperature reconstruction

The two-component WAPLS model was applied to the Hinterburgsee downcore data consisting of 62 samples and 50 chironomid taxa (Figure 3; Heiri *et al.*, 2003). The inferred July air temperatures ranged from 10.1 to 13.8°C (Figure 5a). For samples older than 11500 cal. BP, the model reconstructs low temperatures between 10.1 and 11.0°C. Inferred temperatures in the first part of the Holocene (11500 to 5000 cal. BP) fluctuate strongly and range from 10.4 to 13.8°C. In samples younger than 5000 cal. BP, the inferences tend to be more stable with a July air temperature range of 10.7 to 13.3 °C. Due to the high between-sample variability it is difficult to detect an overall Holocene trend in the reconstructed temperatures. Besides a number of single-sample maxima and minima, two periods with lower temperatures are apparent during the Holocene, i.e., a two-sample event of 10.4–11.1°C from *c.* 10700 to 10500 cal. BP and a four-sample event of 10.6–11.6 °C between *c.* 8300 and 7700 cal. BP. Furthermore, inferred temperatures in the last four samples (600 cal. BP to present) are consistently high, ranging from 12.0 to 12.8°C.

The strong fluctuations of the inferred temperatures in the early Holocene are not surprising as the Hinterburgsee subfossil

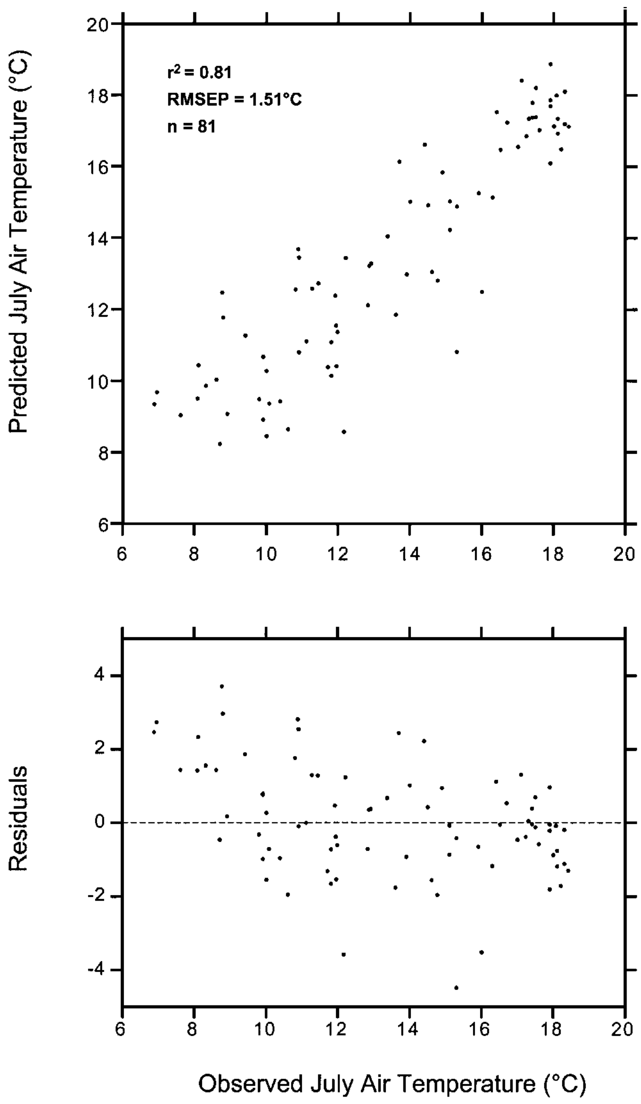

Figure 4 Predicted temperatures and prediction residuals in the chironomid-July air temperature inference model plotted against the observed temperatures. 'RMSEP' indicates the leave-one-out cross-validated root mean square error of prediction, 'r^2' the leave-one-out cross-validated coefficient of determination and 'n' the number of samples.

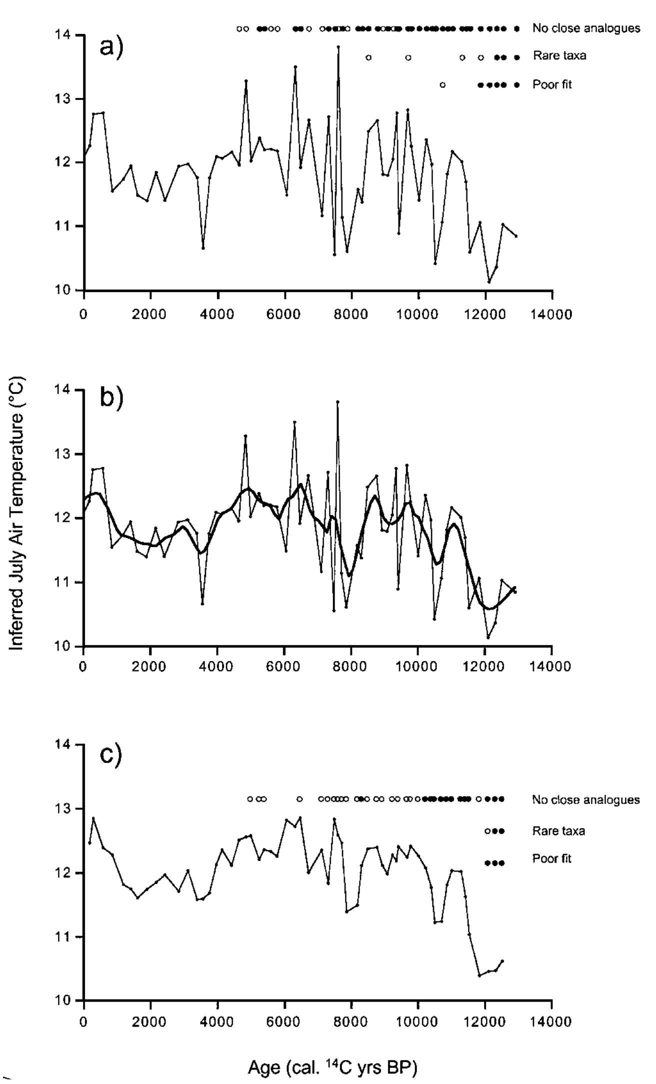

Figure 5 Holocene chironomid-inferred July air temperatures for Hinterburgsee: (a) unsmoothed inferences; (b) LOESS smoother applied to the inferred temperatures; (c) a three-sample running mean applied to the chironomid percentage data prior to reconstruction. The open/solid circles above (a) and (c) indicate samples with no close/no good modern analogue, with more than 5%/more than 10% rare taxa and with a poor/very poor fit to temperature, respectively (see text for details).

chironomid record is characterized by a high between-sample variability of subfossil assemblages (Figure 3; Heiri *et al.*, 2003). This may be partly due to the low number of counts in some early-Holocene samples (seven samples with counts between 27 and 44; Figure 3), as this can cause a high amount of variability or even a bias in chironomid-based temperature reconstruction (Heiri and Lotter, 2001). On the other hand, a large amount of noise irrespective of the count sum seems to be typical of subfossil chironomid records from Swiss subalpine and alpine lakes (Heiri, 2001). In an attempt to increase the signal-to-noise ratio in the temperature reconstruction, we applied two different approaches. First, a LOESS smoother was calculated on the basis of the inferred temperatures and, second, a three-sample running mean was applied to the chironomid percentage data prior to square root transformation and temperature reconstruction (henceforth referred to as reconstruction 1 and reconstruction 2, respectively). The two methods produced very similar results (Figure 5, b and c). In both smoothed temperature reconstructions, Lateglacial temperatures between 10.4 and 10.9°C were inferred. The earliest Holocene is marked by a strong increase of July air temperatures, reaching a plateau of *c.* 11.9–12.0°C. A first major temperature reversal is apparent between 10700 and 10500 cal. BP with temperatures of 11.2–11.3°C. From 10200 to 4000 cal. BP, inferred temperatures were generally between 11.9 and 12.8°C, although a second temperature reversal with temperatures of 11.1–11.5°C is apparent between *c.* 8200 and 7700 cal. BP. Around 4000 cal. BP, temperatures drop again and reach a local minimum of 11.5–11.6°C at *c.* 3600–3300 cal. BP. In younger samples, the inferred July air temperatures generally lie between 11.5 and 12.0°C, but they increase again during the last *c.* 1000 years to values around 12.4–12.8°C.

Numerical evaluation

An important consideration when applying quantitative organism-based reconstruction methods to palaeoecological data is the numerical evaluation of the results (Birks, 1998). Inference models produce numbers even if the modern calibration data set does not contain the necessary ecological information to reliably reconstruct past environments from the fossil samples of interest. Following Birks *et al.* (1990), Birks (1995) and Birks (1998), we therefore calculated for every sample goodness-of-fit and analogue statistics, the percentage of taxa not occurring in the modern data set, the percentage of rare taxa and the sample specific RMSEP.

Of all samples in the Hinterburgsee subfossil chironomid record, 66% have no close analogue and 48% no good analogue in the modern data, although only samples older than 4000 cal. BP are affected by analogue problems (Figure 5a). Only a single Holocene sample shows a poor fit to July air temperature, whereas all Lateglacial samples have a very poor fit to temperature (Figure 5a). The maximum abundance of taxa not occurring in the modern data set was below 2.5% in any given sample of the Hinterburgsee record. However, three early-Holocene and four Lateglacial samples have more than 5% chironomid counts of rare taxa and three Lateglacial samples more than 10% (Figure 5a). The maximum percentage of rare taxa in any sample is 20%. The sample-specific RMSEPs range from 1.56 to 1.79°C and are only slightly higher than the overall error estimate of the model (103–120%).

In the smoothed percentage data, all validation criteria are improved. Only 55% of all samples remain with no close analogue and 22% without good analogue (Figure 5c). Furthermore, samples with a poor or very poor fit to temperature and with more than 5% rare taxa are restricted to the Lateglacial. Sample-specific estimates for the RMSEP range from 1.55 to 1.70°C (103–112% of the overall RMSEP of the model) and in 90% of the samples these are smaller than in the unsmoothed chironomid record.

Discussion

Reliability of inferred temperatures

During the Holocene, many samples in the Hinterburgsee subfossil chironomid record do not have close or good analogues in the modern chironomid data. In contrast, samples with a poor fit to temperature are restricted to the Lateglacial and in some few cases to the earliest Holocene. Furthermore, at least 80% of the subfossil taxa in any one sample are well represented in the modern calibration data set. The fact that the analogue situation is markedly improved in the smoothed percentage data suggests that the poor analogues are caused to a significant extent by the high variability and by low count sums in the chironomid data, rather than by a Holocene chironomid fauna uncommon in modern lakes. In Hinterburgsee, a number of taxa common in the Lateglacial survived almost 2000 years into the Holocene (Heiri *et al.*, 2003). This produced mixed faunal assemblages of alpine and subalpine elements found nowhere in modern Swiss lakes, thereby causing the poor analogue situation in the earliest Holocene. Nevertheless, WAPLS performs relatively well in poor analogue situations

(Birks, 1998). As more than 95% of the chironomids in any sample in the smoothed Holocene record are well represented in the modern data and the inferred 'poor analogue' temperatures are not at the edge of the temperature gradient, it is expected that the smoothed reconstruction provides reasonable temperature estimates even for the earliest Holocene. However, it should be remembered that smoothing invariably introduces a bias to the reconstruction, as the timescale is slightly distorted and extreme values are corrected towards the local mean.

Long-term trends

Towards the end of the Younger Dryas mean July air temperatures around 10.4–10.9°C are inferred at Hinterburgsee (Figure 5, b and c). Temperature reconstructions from nearby Gerzensee (603 m a.s.l.), based on pollen and Cladocera, infer mean summer (June, July, August) air temperatures of 9–10°C during this period (Lotter *et al.*, 2000). At present, mean July air temperatures in the Swiss Alps are highly correlated to and approximately 1°C higher than mean summer air temperatures (A.F. Lotter, unpublished data). Thus, if the same relationship existed during the Lateglacial this would imply Younger Dryas July air temperatures around 10–11°C at Gerzensee. In the northern Swiss Alps, the decrease in present-day July air temperatures with altitude is estimated as being 0.6°C per 100 m (Livingstone *et al.*, 1999). Assuming comparable lapse rates for the Lateglacial period, the chironomid-inferred temperatures at Hinterburgsee corrected to an altitude of 600 m a.s.l. would therefore be *c.* 16°C, or 5–6°C warmer than those inferred for Gerzensee. However, the Lateglacial samples in the Hinterburgsee chironomid record are strongly affected by analogue problems, by a comparatively high proportion of rare taxa and by a 'poor fit' to temperature. Furthermore, the inferred temperatures may already be influenced by the edge effects of the chironomid-temperature calibration model. Nevertheless, the large discrepancy between the reconstructions raises the question whether the Younger Dryas summer temperature estimates of Lotter *et al.* (2000) may be too low. Further Lateglacial temperature reconstructions based on models less affected by edge effects and analogue problems are necessary to resolve this issue.

With the exception of two distinct short-term cool periods, the smoothed Holocene temperature reconstruction of Hinterburgsee can be split into three parts (Figure 5, b and c): (1) the early to mid-Holocene (11500–4000 cal. BP) with temperatures between 11.9 and 12.8°C, *c.* 0.6–1.6°C warmer than today; (2) the late Holocene (3500–1000 cal. BP) with temperatures between 11.5 and 12°C, only 0.2 to 0.7°C warmer than today; and (3) the last millennium BP, again with higher temperatures reaching 12.4 to 12.8°C.

Due to changes in the Earth-Sun geometry, the maximum Holocene summer insolation at northern latitudes was reached at *c.* 9000 cal. BP (Kutzbach and Webb, 1993). Congruously, Holocene climate reconstructions in Europe generally infer high summer temperatures in the early and mid-Holocene and lower temperatures in the past few millennia. In western Scandinavia, the highest Holocene temperatures based on palaeobotanical and glacier equilibrium-line reconstructions are generally inferred for the period between *c.* 9500 and 5000–6000 cal. BP, with a decreasing trend during the rest of the Holocene (e.g., Dahl and Nesje, 1996; Matthews *et al.*, 2000). The maximum treeline elevation in the Swiss Alps has been inferred from *c.* 9000–8000 cal. BP to 5400–5000 cal. BP (Lang, 1993; Wick, 1994; Tinner *et al.*, 1996). However, the first human induced lowering of treeline may have taken place as early as *c.* 5500 cal. BP (Lang, 1993; Tinner *et al.*, 1996) and, therefore, climatological interpretations of the treeline depressions since the mid-Holocene may be biased by local human activity. At Hinterburgsee, a decrease in the smoothed temperature reconstructions from high values in the early and mid-Holocene to lower values in the late Holocene takes place fairly abruptly between *c.* 4000 and 3700 cal. BP (note, however, that this trend is strongly influenced by a single sample; Figure 5). This is about 1000–1500 years later than might be inferred from treeline depressions. Nevertheless, a major change in Holocene climate between *c.* 4000 and 3500 cal. BP is supported by other European summer air temperature reconstructions: After 6000 years of virtually having been absent, glaciers in the eastern Swiss Alps formed again between *c.* 4000 and 3500 cal. BP and have persisted during the rest of the Holocene (Leemann and Niessen, 1994). According to Leemann and Niessen (1994), this is most likely a consequence of lower summer temperatures. Similarly, Nesje *et al.* (2001) present results indicating glacier advances in western Norway after 4000 cal. BP. Furthermore, Anderson *et al.* (1998) describe an abrupt shift to wetter and possibly cooler conditions in northern Scotland between 3900 and 3500 cal. BP. At Hinterburgsee, inferred temperatures remain below 12°C between 3500 and 1000 cal. BP, only to rise again during the last millennium BP. Such a strong increase in summer temperatures is not evident in other temperature reconstructions. On the contrary, the past few hundred years before the twentieth century are considered to be among the coolest experienced during the Holocene (Bradley, 2000). Obviously, the Hinterburgsee chironomid-temperature reconstruction fails to track this cooler climate. Palaeobotanical evidence indicates strongly increased human activity near Hinterburgsee (opening of the catchment vegetation and pasturing) starting from *c.* 1000 cal. BP (Heiri *et al.*, 2003). The presence of humans and livestock in a lake's catchment can increase the nutrient loading of the lake, thereby changing the trophic conditions to be more typical of sites of lower elevation. The temporal agreement between the increasing human activity near Hinterburgsee and the rise in chironomid-inferred temperatures therefore suggests that this recent trend is a bias due to anthropogenic impact on the lake ecosystem.

Climate reversals

The two strongest Holocene climatic fluctuations in the chironomid reconstruction are the decrease of inferred July air temperatures at *c.* 10700–10500 and at *c.* 8200–7700 cal. BP (henceforth referred to as events A and B). In consideration of the uncertainty in our age-depth model, cold periods with a similar age as event A have been inferred from the Swiss and Austrian Alps (e.g., Patzelt, 1977; Wick and Tinner, 1997; Haas *et al.*, 1998) and from Western Scandinavia (e.g. Dahl and Nesje, 1994; Matthews *et al.*, 2000). In central Europe, the timing of a major early-Holocene cold event has been reported as 10750–10200 cal. BP (Haas *et al.*, 1998) and in southern Norway and the North Atlantic region as 10300 cal. BP (Matthews *et al.*, 2000; Björck *et al.*, 2001). The decrease in summer air temperature has been estimated to 0.8°C (Haas *et al.*, 1998) for the Swiss Alps, which agrees well with both of our smoothed temperature reconstructions, suggesting a decline in July air temperature of 0.6–0.8°C (note, however, that in the unsmoothed temperatures the decrease is 1.7°C!). The beginning of event B coincides with a widely reported temperature decline around the North Atlantic. Oxygen isotopes measured in the Greenland ice cores and in lake marls in the Alpine foreland of southern Germany indicate a significant annual temperature decrease at 8200 cal. BP, lasting about 100 to 200 years (Alley *et al.*, 1997; von Grafenstein *et al.*, 1998) and estimated to be of a decline of 1.7°C in mean annual temperature in southern Germany (von Grafenstein *et al.*, 1998). A cold event of a similar age is well represented in many northern and central European reconstructions of Holocene summer air temperature (e.g., Dahl and Nesje, 1996; Wick and Tinner, 1997; Haas *et al.*, 1998; Matthews *et al.*, 2000; Nesje and Dahl, 2001) and estimated to be of a summer temperature decrease of between 0.8°C in the Alps (Haas *et al.*, 1998) and 1.2°C in Norway (Dahl and Nesje, 1996). At Hinterburgsee this cooling episode (event B) starts at *c.* 8200 cal. BP and, depending on the smoothing of the reconstruction, lasts a minimum of 300–400 years. Smoothed chironomid inferred temperatures indicate a decrease of July air temperatures of about 1°C, but again the decrease in unsmoothed temperatures is stronger and amounts to *c*. 2°C (Figure 5). It is intriguing that the duration of event B at Hinterburgsee is significantly longer than the cold event registered in oxygen-isotope measurements in Greenland and in southern Germany (Alley *et al*., 1997; von Grafenstein *et al*., 1998) and this raises the question if there existed a longer period of cooler summer temperatures around 8000 cal. BP in Europe than has previously been assumed based on isotope measurements. However, three of the radiocarbon samples in our age-depth model have an age close to 8200 cal. BP (Figure 2) and an alternative explanation may be that our model underestimates the sedimentation rate during this part of the core and therefore overestimates the duration of this cold event.

Summary and conclusions

(1) On the basis of a chironomid-air temperature calibration model, low July air temperatures of 10.4–10.9°C were reconstructed at Hinterburgsee for the end of the Younger Dryas, high temperatures of 11.9–12.8°C during the early and mid-Holocene (11500–4000 cal. BP) and again lower temperatures of 11.5–12.0°C during the late Holocene (3500–1000 cal. BP). Higher temperatures are again inferred from the youngest samples (after 1000 cal. BP). Since there is evidence of strong regional human impact near Hinterburgsee during this period, and since this warming trend runs contrary to other summer-temperature reconstructions, we consider it to be an artefact of local human activity.

(2) According to the smoothed temperature reconstructions the most significant climatological events at Hinterburgsee were two periods of lower July air temperatures of 11.1–11.4°C during the early and mid-Holocene (*c*. 10700–10500 and 8200–7700 cal. BP) and the abrupt shift to cooler July air temperatures at *c*. 4000–3700 cal. BP.

(3) The reconstructed Holocene temperature changes are within the prediction error of the chironomid-July air temperature inference model. Furthermore, the amplitudes of the fluctuations are certainly influenced by the smoothing of the inferred temperature values (for reconstruction 1) or of the raw chironomid percentage data (for reconstruction 2). Nevertheless, the improved evaluation statistics of reconstruction 2 indicate that due to a high variability in the Hinterburgsee subfossil chironomid record the smoothed temperatures provide a more reliable temperature estimate than the unsmoothed inferences.

(4) Clearly a higher temporal resolution is needed to reduce the bias of smoothing on our temperature inferences and to fully quantify the extent and duration of major Holocene summer-temperature fluctuations in the Swiss Alps. Nonetheless, our results underline the potential of chironomid-based temperature inference models to track not only the high amplitude climatic reversals of the Lateglacial, but also the weaker climate events in the Holocene.

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