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A chironomid-based reconstruction of late glacial summer temperatures in the southern Carpathians (Romania)

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ABSTRACT

Late glacial and early Holocene summer temperatures were reconstructed based on fossil chironomid assemblages at Lake Brazi (Retezat Mountains) with a joint Norwegian–Swiss transfer function, providing an important addition to the late glacial quantitative climate reconstructions from Europe. The pattern of the late glacial temperature changes in Lake Brazi show both similarities and some differences from the NGRIP $\delta^{18}O$ record and other European chironomid-based reconstructions. Our reconstruction indicates that at Lake Brazi (1740 m a.s.l.) summer air temperature increased by ~2.8°C at the Oldest Dryas/Bølling transition (GS-2/GI-1) and reached 8.1–8.7°C during the late glacial interstade. The onset of the Younger Dryas (GS-1) was characterized by a weak (<1°C) decrease in chironomid-inferred temperatures. Similarly, at the GS-1/Holocene transition no major changes in summer temperature were recorded. In the early Holocene, summer temperature increased in two steps and reached ~12.0–13.3°C during the Preboreal. Two short-term cold events were detected during the early Holocene between 11,480–11,390 and 10,350–10,190 cal yr BP. The first cooling coincides with the Preboreal oscillation and shows a weak (0.7°C) temperature decrease, while the second is characterized by 1°C cooling. Both cold events coincide with cooling events in the Greenland ice core records and other European temperature reconstructions.

Introduction

During the late glacial period (LG; *ca.* 14,700–11,500 cal yr BP) a series of abrupt, decadal and century-long cool and warm events have been described in the Northern Hemisphere (Björck et al., 1998; Rasmussen et al., 2006). These rapid climatic changes were ascribed to perturbations of the thermohaline circulation in the North Atlantic region caused by periodic meltwater fluxes during deglaciation (Alley et al., 2003). These major climatic events are well-represented in various proxy records from western and northwestern Europe and can be detected in the NGRIP $\delta^{18}O$ record from Greenland as well (e.g., Björck et al., 1998; Brooks, 2006; Larocque and Finsinger, 2008; Ilyashuk et al., 2009). Nevertheless, few LG proxy records are available from east-central Europe and especially the Carpathian Mountains (e.g., Willis et al., 1995; Feurdean et al., 2007; Tantau et al., 2009), an area located far from the North Atlantic. Model simulations suggest that this continental interior region was less affected by LG cooling events of the North Atlantic. In the case of the Bølling/Allerød–Younger Dryas transition (GI-1/GS-1; Björck et al., 1998), for example, summer temperatures were modelled to decline only 2°C in the southern Carpathians (Renssen and Isarin, 2001). Regarding the climate of this region, both Constantin et al. (2007) and Popa and Kern (2009) suggested that the climate of the southern Carpathians has been strongly influenced by warm and dry southeasterly air masses in addition to the Atlantic air masses that carry precipitation from the west.

Fossil remains of non-biting midges (Diptera: Chironomidae) have widely been used for quantitative paleotemperature reconstruction (e.g., Walker et al., 1991; Brooks, 2006). Chironomids are dominant members of aquatic macroinvertebrate communities both in lotic and lentic habitats (Pinder, 1986). Additionally, their chitinous head capsules preserve well in lake sediments and can be identified to species morphotypes or generic level (Brooks et al., 2007). Several

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authors have shown that the composition of chironomid assemblages is strongly influenced by surface-water and summer air temperature (Walker et al., 1991; Brooks, 2006; Eggermont and Heiri, in press). Based on this relationship, chironomid temperature transfer functions have been developed for several different geographical regions (e.g., Lotter et al., 1997; Walker et al., 1997; Brooks and Birks, 2001; Larocque et al., 2001; Heiri and Lotter, 2010) and have been successfully used to reconstruct past climatic changes during the LG and early Holocene (e.g., Brooks and Birks, 2000; Peyron et al., 2005; Heiri et al., 2007; Larocque and Finsinger, 2008; Ilyashuk et al., 2009). In addition, chironomid-inferred temperatures show good agreement with meteorological data (Larocque and Hall, 2003; Larocque et al., 2009), indicating the usefulness of chironomid remains in temperature reconstruction.

In this study we focus on chironomids recovered from the LG and early Holocene sediment of a mountain lake formed during the last glaciation, Lake Brazi (Tăul dintre Brazi) in the South Carpathian Mountains (Figures. 1 and 2). We carried out this study within the multi-proxy paleoecological project PROLONGE (Magyari et al., 2009a). The project focuses on ecosystem response to rapid climate change at the GS-2/GI-1 and GS-1/GI-1 transitions (Björck et al., 1998) in the Retezat Mountains. Reconstructions of past environmental change based on other proxies from the same sediment sequence have either been published or are in press, for example, LG vegetation changes and treeline oscillations in response to rapid climate change (Magyari et al., 2009b), and diatom response to LG climatic oscillation (Buczkó et al., 2009). Here we present a high-resolution LG chironomid record from Lake Brazi. The main objectives of the paper are (1) to describe compositional changes in the chironomid assemblages during the LG and early Holocene; (2) to reconstruct quantitatively late glacial mean July air temperatures using the joint Norwegian–Swiss transfer function; and (3) to compare the reconstructed temperatures with other LG records from the region and from Europe.

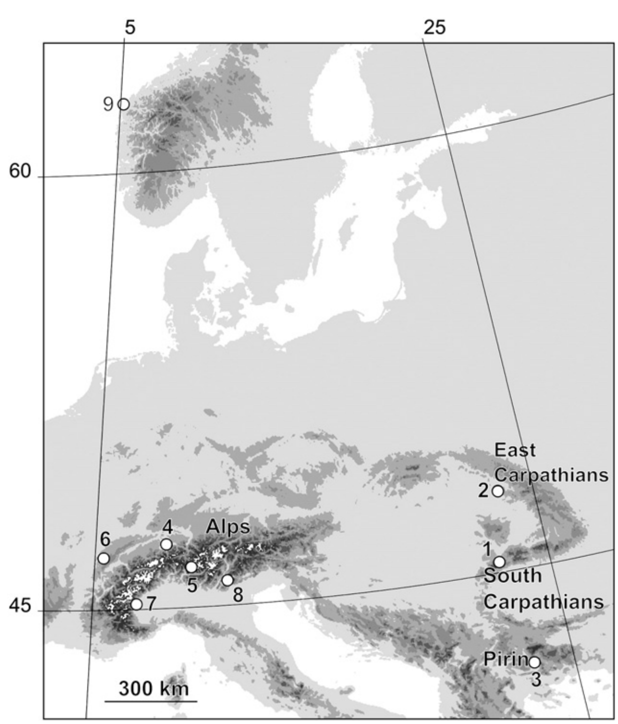

Figure 1. Location of the studied lake in the southern Carpathians and those used for comparisons from elsewhere in Europe. 1 = Lake Brazi, Romania (this study); 2 = Precula Tiganului and Steregoiu, Romania (Feurdean et al., 2008a); 3 = Lake Dalgoto, Bulgaria (Stefanova et al., 2003); 4 = Egelsee, Switzerland (Larocque-Tobler et al., 2010); 5 = Maloja Riegel, Switzerland (Ilyashuk et al., 2009); 6 = Lake Lautrey, France (Heiri and Millet, 2005; Peyron et al., 2005); 7 = Lago Piccolo di Avigliana, Italy (Larocque and Finsinger, 2008); 8 = Lago di Lavarone, Italy (Heiri et al., 2007); 9 = Kråkenes Lake, Norway (Brooks and Birks, 2000).

Study site

The Retezat Mountains are located in the southern Carpathians (Figure 1). They are among the highest massifs and include the highest number of mountain peaks over 2000 m in Romania. In total, 58 permanent lakes of glacial origin are situated in the Retezat, mainly between 1900 and 2300 m a.s.l. (Jancsik, 2001). Lake Brazi (Figure 2; 1740 m a.s.l., 45°23′47″N, 22°54′06″E, 0.5 ha, 1 m water depth) is the lowest altitude glacial lake, at the western marginal side of the Galeş glacial valley in a mixed Norway spruce (*Picea abies*)–stone pine (*Pinus cembra*) forest. Vegetation on the lakeshore consists of *Sphagnum* spp., *Juncus filiformis*, *Eriophorum vaginatum*, *Vaccinium myrtillus* and *V. vitis-ideae*. The eastern part of the lake basin is covered by a floating mat of *Pinus mugo*, *Rhododendron myrtifolium* and various *Sphagnum* species.

The climate of the Retezat is temperate continental, influenced by Mediterranean and oceanic air masses (Jancsik, 2001). As a result, it is one of the wettest massifs in the Romanian Carpathians (1400 mm yr^{-1} at 1500–1600 m a.s.l.). The mean annual temperature is 6°C in the foothill zone but drops to −2°C on the highest peaks (2500 m a.s.l.). January is the coldest month, having a mean temperature of −10°C, while July is the warmest month when mean temperatures range between 6 and 16°C. Present-day July temperatures are around 11°C at 1740 m a.s.l. on the northern slope of Retezat. The 10°C July isotherm runs parallel to the upper tree limit, at an altitude of 1900 m a.s.l. on the southern flank and around 1800 m a.s.l. on the northern flank (Jancsik, 2001).

Snow duration is 100 days at low altitudes and approximately 170 days at 2000 m a.s.l. Snow persists in some places even during summer and sporadic permafrost occurs at some high elevation sites situated in favorable morphoclimatic conditions (Kern et al., 2004). Stone glaciers are present at high altitude in the major southern glacial valley (Urdea, 2004).

Methods

Sediment sampling, chronology and laboratory analyses

A 500-cm sediment core (TDB-1) was taken in the central part of Lake Brazi in August 2007 with a Livingstone corer (chamber length 100 cm, diameter 7 cm). At the core location water depth was 110 cm. Here we discuss only the late glacial and early Holocene part (the bottom 1 m) of this core. Sediment lithology was examined and documented in the laboratory.

The core was subsampled at 1 cm intervals; 1-cm^3 samples were combusted at 550°C for 3 h for loss-on-ignition (LOI) analysis. LOI was used to estimate organic matter content of the sediment (Heiri et al., 2001).

A chronological framework for the LG part of TDB-1 was established using seven AMS ^{14}C age determinations on terrestrial plant macrofossils (Table 1). An age–depth curve for the TDB-1 core was constructed using a weighted non-linear regression function and extrapolation below the last dated sediment level. For details of the age–depth modelling see Magyari et al. (2009a) and Figure 3.

Chironomid analysis

For chironomid analysis, 1 to 4.5 cm^3 of sediment was taken at 2-cm intervals. Subsamples were deflocculated in 10% KOH and heated at 60°C for 20 min. Afterwards the sediment was sieved with a 100-μm mesh. Chironomid larval head capsules were picked out in a Bogorov counting tray (Gannon, 1971) under the stereomicroscope at 40–50× magnification. Larval head capsules were mounted on microscope slides in Euparal® mounting medium for microscopic identification.

Figure 2. Photograph of Lake Brazi (Photo: Enikő K. Magyari).

Chironomid head capsule concentration was estimated by counting all head capsules in the subsamples. At least 45 head capsules were identified in each sample, except in six samples (at core depths of 546, 592, 594, 596, 598 and 600 cm) that contained only 11–24 head capsules. However, most of the samples contained more than 45 head capsules, so they provided a representative count for quantitative analysis (Heiri and Lotter, 2001). Identification of chironomid head capsules followed Wiederholm (1983), Rieradevall and Brooks (2001), and Brooks et al. (2007).

Plotting, numerical analyses and temperature reconstruction

The chironomid relative abundance diagram was produced using TILIA software (Grimm, 1991) and it was zoned by optimal splitting by information content with the program psimpoll 3.00 (Bennett, 2005). To estimate major changes in the chironomid assemblages along the temperature gradient, a detrended correspondence analysis (DCA) was done using CANOCO version 4.5 (ter Braak and Šmilauer, 1998). For ordination, the percentage species data were square root transformed and rare taxa down-weighted. The gradient length of the first DCA axis was 4.3 SD units and supported the use of unimodal methods for ordination of chironomid data (Birks, 1995).

Mean July air temperature (T_{VII}) was reconstructed quantitatively using weighted averaging partial least-squares regression model (WA-PLS; ter Braak and Juggins, 1993) based on a joint Norwegian–Swiss chironomid temperature calibration dataset (Heiri et al., in press). This combined chironomid dataset includes surface sediment samples from 274 lakes, covering wider altitudinal, latitudinal and T_{VII} (3.5–18.4°C) gradients than the Swiss or the Norwegian models individually (Brooks and Birks, 2000; Heiri et al., 2003; Heiri and Lotter, 2005, 2010). In this study we applied a combined model rather than only the Swiss transfer function since there are several taxa in the Brazi record that are not represented in the Swiss calibration set. Furthermore, the joint model is based on lakes covering a wide range of lake water pH values, whereas the Swiss dataset covers a limited range of pH conditions. The T_{VII} reconstruction and sample-specific prediction errors (SSPEs) were calculated using the program C2 (Juggins, 2007).

Results and interpretation

Chronology, sediment stratigraphy and LOI

In Lake Brazi all ^{14}C ages (Table 1) showed good agreement with the age inferred by the pollen stratigraphy. In this core, 1-cm sample resolution translates to a mean temporal resolution of about 74–104 years for the LG (between *ca.* 15,755–11,550 cal yr BP) and 16–20 years for the early Holocene part of the sediment (Magyari et al., 2009a). The 100-cm-long section of core TDB-1 was classified into seven lithostratigraphic units (Figure 3). The bottom three sedimentary units (units 1–3) were characterised by middle-gray silt and

Table 1
Radiocarbon dates from Lake Brazi (TDB-1). AMS ^{14}C dates were obtained from the Poznań Radiocarbon Laboratory, Poland (Poz).

Core	Laboratory code	Dated material	Depth (cm)	^{14}C age, yr BP	Calibrated range, yr BP (2σ)	Remarks
TDB-1	Poz-26111	*Picea abies* needles	505	8810 ± 50	9670–9966	Suspect
TDB-1	Poz-31714	*Pinus mugo* needles	521	9150 ± 50	10,223–10,432	
TDB-1	Poz-26112	*Picea abies* cone	545	9610 ± 50	10,764–11,165	
TDB-1	Poz-31715	*Pinus mugo* needles	557	9980 ± 100	11,216–11,618	
TDB-1	Poz-31716	charcoal	569	10,870 ± 70	12,598–12,925	
TDB-1	Poz-27305	*Pinus sp.* needles (2)	578	11,590 ± 60	13,287–13,620	
TDB-1	Poz-26113	*Picea abies* cone scales	591	9690 ± 50	11,067–11,225	Outlier

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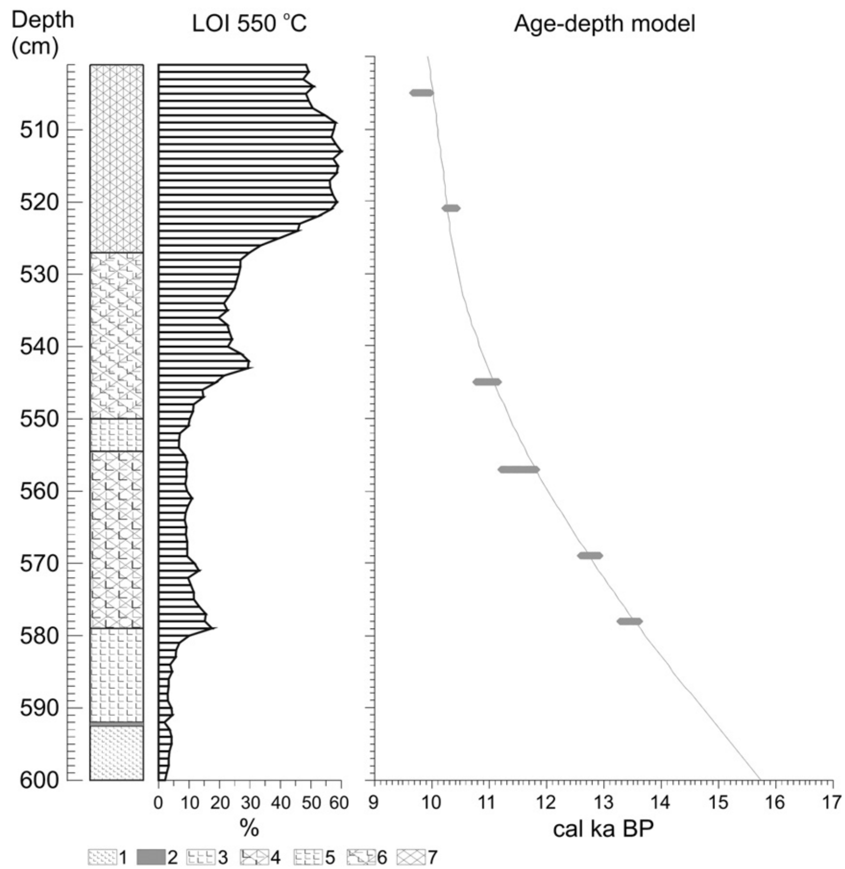

Figure 3. Lithostratigraphy (left), organic matter content as percentage loss-on-ignition at 550°C (center) and age–depth model (right) of the late glacial and early Holocene part of TDB-1. 1 = middle-gray–light brown silty clay; 2 = dark gray sand lens; 3 = middle-gray silty clay with faint lamination; 4 = middle-gray–middle-brown clay gyttja with increased organic content; 5 = light gray–light brown silty clay; 6 = middle-gray–middle-brown silty gyttja; 7 = dark brown fine gyttja rich in plant macrofossils.

clay with a sand lens in unit 2. LOI values indicated very low organic content in these sediment units (2.1–4.4%) with an increase starting in the top part of unit 3, at *ca.* 14,000 cal yr BP (583 cm) and reaching a maximum 10% at *ca.* 13,630 cal yr BP (579 cm). These changes suggest gradually increasing in-lake and lakeshore productivity during the second part of the Bølling/Allerød interstade (GI-1).

The next sediment unit (unit 4) included the second part of GI-1 and the entire Younger Dryas (GS-1). The sediment color in this unit was middle-gray, middle-brown clay gyttja and the average organic content was higher (11%) than in the lower units. The highest organic content (*ca.* 15.5–17%) was detected between *ca.* 13,350–13,630 cal yr BP (576–579 cm). These data suggest a moderate productivity decrease during GS-1 in and around the lake.

Sediment unit 5 was a thin layer (4.5 cm) of light gray, light brown silty clay with decreased organic content (7%). Low organic content of the sediment near to the Younger Dryas/Holocene boundary (554.5 cm; at *ca.* 11,650 cal yr BP) might reflect accelerated erosion caused by meltwater input from locally melting snowfields.

Unit 6 was a transitional silty gyttja layer rich in plant macrofossils with gradually increasing organic content up to 26%. Gyttja sediments rich in plant macrofossil, charcoal and wood remains accumulated in unit 7 (from *ca.* 10,370 cal yr BP) and LOI values increased to 56–58%, suggesting high in-lake and lakeshore productivity.

Chironomid record

Altogether, 19 chironomid taxa were identified from the sediment and 15 taxa had an abundance >2% in at least one sample. Rare taxa with abundance <2% were *Diamesa*, *Corynoneura arctica*-type, *Cricotopus sylvestris*-type and *Polypedilum nubeculosum*-type. Four statistically significant chironomid zones (zone boundaries at *ca.* 14,220, 10,980 and 10,210 cal yr BP) were identified and a further three non-significant subzones were determined based on characteristic changes in assemblage composition (Figure 4).

The first significant zone (Zone 1; >14,220 cal yr BP) was divided into two subzones (Zone 1a and Zone 1b). Zone 1a (600–591 cm; *ca.* 15,760–14,800 cal yr BP) was dominated by cold stenothermic taxa, such as *Diamesa*, *Pseudodiamesa* and *Micropsectra radialis*-type. Chironomid concentrations were very low in this part of the sediment. Thereafter, in Zone 1b (591–585 cm; *ca.* 14,800–14,220 cal yr BP) *Diamesa* disappeared and the relative frequency of *Pseudodiamesa* decreased. While the abundance of *M. radialis*-type decreased at the beginning of this subzone, it again reached high relative abundances (about 80%) at *ca.* 14,300 cal yr BP (586 cm). The first appearance of two further taxa typical for subalpine lakes (*Tanytarsus lugens*-type, *Micropsectra insignilobus*-type) and other chironomids with relatively wide temperature tolerance, such as *Procladius*, *Zavrelimyia* type A, *Psectrocladius sordidellus*-type and *Tanytarsus mendax*-type, is apparent within this zone.

The second significant zone (Zone 2; *ca.* 14,220–10,980 cal yr BP) was divided into three subzones (Zones 2a; 2b and 2c). Zone 2a (585–569 cm; *ca.* 14,220–12,740 cal yr BP) was dominated by the cold stenothermous taxon *T. lugens*-type and by *Procladius*, characterised by broad thermal tolerance. The cold-adapted *Pseudodiamesa* and *M. radialis*-type disappeared in this subzone, and several other taxa appeared for the first time or were present in increased abundance, such as *M. insignilobus*-type, *Zavrelimyia* type A, *Paratanytarsus austriacus*-type and *P. sordidellus*-type. In Zone 2b (569–549 cm; *ca.* 12,740–11,300 cal yr BP) *M. insignilobus*-type, with a wide thermal tolerance, increased and reached its maximum abundance. In addition, a cold stenothermous *T. lugens*-type dominated this subzone. Later on, in Zone 2c (549–543 cm; *ca.* 11,300–10,980 cal yr BP) *T. lugens*-type

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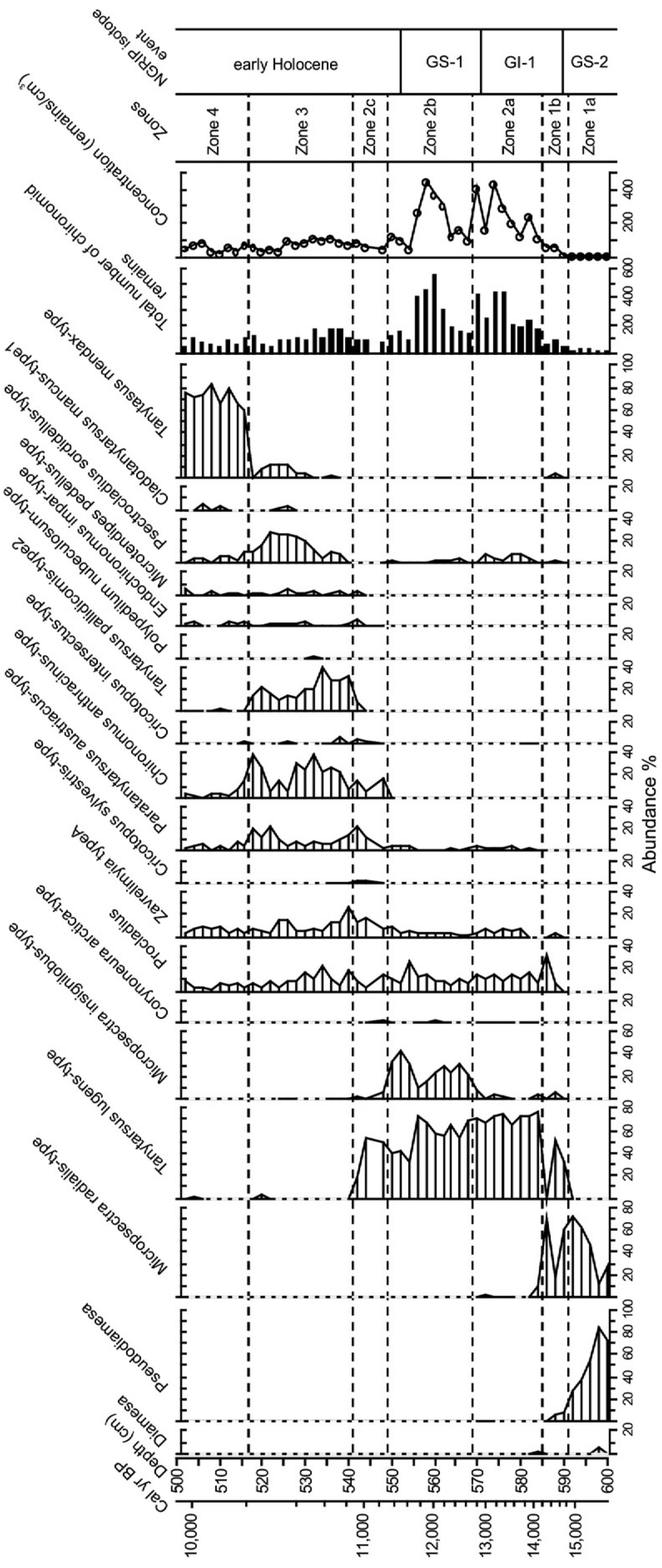

Figure 4. Chironomid relative frequency diagram (including all chironomid taxa) and zones for the chironomid stratigraphy from Lake Brazi (Retezat Mountains, Romania) with NGRIP event stratigraphy (Björck et al., 1998).

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became the most abundant taxon, while *M. insignilobus*-type decreased in abundance and became more sporadic before finally disappearing by *ca.* 11,000 cal yr BP. Zone 2c includes four taxa that attained abundances near 20%: *Procladius*, *Zavrelimyia* type A, *P. austriacus*-type and *Chironomus anthracinus*-type. Chironomini taxa (*C. anthracinus*-type, *Endochironomus impar*-type and *Microtendipes pedellus*-type) usually indicative of relatively warm climatic conditions first appeared in this subzone. Total chironomid concentrations were the highest in Zones 2a and 2b, while they significantly decreased in Zone 2c probably as a result of the increasing sediment accumulation rates (Figure 3).

The third significant zone was Zone 3 (543–517 cm; *ca.* 10,980–10,200 cal yr BP). Important changes in assemblage composition include the disappearance of cold-adapted *T. lugens*-type and *M. insignilobus*-type, an increase in relative abundance of *C. anthracinus*-type and warm-adapted *Tanytarsus pallidicornis*-type2, as well as reappearance of *P. sordidellus*-type and *T. mendax*-type. Chironomid concentration decreased again slightly towards the end of Zone 3.

Zone 4 (517–500 cm; *ca.* 10,200–9970 cal yr BP) was dominated by *T. mendax*-type, a taxon which has broad thermal tolerance. Several taxa in this zone have low relative abundances (<10%): *Procladius*, *Zavrelimyia* type A, *P. austriacus*-type, *C. anthracinus* type, *E. impar*-type, *M. pedellus*-type, *P. sordidellus*-type and *Cladotanytarsus mancus*-type1. Chironomid concentrations decreased in the lower part of this zone followed by a moderate increase in the second half of Zone 4 (from *ca.* 10,050 cal yr BP onwards).

Summer temperature reconstruction

The first DCA axis explains 37.1% of cumulative variance in the chironomid data (Figure 5). During the Oldest Dryas (GS-2) the temperature reconstruction suggested mean July temperatures around 5.2–5.3°C. At *ca.* 14,700 cal yr BP, summer temperatures started to increase rapidly and reached 8.1°C within approximately 200 years of the onset of the Bølling interstade (GI-1e; *ca.* 14,500 cal yr BP). Between *ca.* 13,700 and 11,480 cal yr BP, mean July temperatures fluctuated around 8.1–8.6°C. Within this period the Younger Dryas cooling (GS-1; *ca.* 12,860–11,500 cal yr BP) was weakly expressed (<1°C decline in T_{VII}) in the Lake Brazi temperature record. At the same time, a small decline on the DCA curve was visible at *ca.* 12,820 cal yr BP, at the onset of the GS-1 stade (Figure 5).

At the beginning of the early Holocene (*ca.* 11,500 cal yr BP) reconstructed July temperatures slightly increased to 8.8°C followed by a small decline at *ca.* 11,480 cal yr BP to 8.1°C. Later on, at *ca.* 11,390 cal yr BP summer temperatures increased again and reached 9.2°C by 11,240 cal yr BP, followed by a further increase to 11.9°C by 10,830 cal yr BP. Between *ca.* 10,350–10,200 cal yr BP a further short-term (150 years) cooling was detected with an amplitude of about 1°C (to 10.9°C). After this cold event, July air temperatures fluctuated around 12.0–13.3°C in the upper part of the record (between *ca.* 10,190 and 9970 cal yr BP).

Discussion

Faunistic changes at Lake Brazi

Characteristic changes in chironomid assemblages at Lake Brazi were observable during the late glacial and early Holocene. One of the most interesting changes occurred at the beginning of the LG interstade, at *ca.* 14,700 cal yr BP, when cold stenothermous chironomids such as *Pseudodiamesa* and *M. radialis*-type were replaced by taxa typical of subalpine lakes or with a wide thermal tolerance, such as *M. insignilobus*-type, *Procladius* or *Zavrelimyia* type A. This shift leads to a clear increase in chironomid-inferred temperatures in the Lake Brazi record (Figure 5). At the onset of the Younger Dryas (GS-1) chronozone, there is a clear shift in dominant chironomid taxa, which is also reflected in DCA axis 1 sample scores, but this change is not apparent in estimates of past summer air temperatures, which remain relatively stable. The Younger Dryas chironomid fauna was mainly characterized by the dominance of taxa typical of subalpine and lower alpine lakes, such as *T. lugens*-type and *M. insignilobus*-type, while in other central European chironomid records other taxa were also dominant in this period, such as *Microtendipes*, *M. radialis*-type and *P. sordidellus*-type (e.g., Heiri and Millet, 2005; Larocque and Finsinger, 2008; Ilyashuk et al., 2009; Larocque-Tobler et al., 2010). Contrary to our results, in these records the GS-1 cooling was well expressed in the temperature reconstructions.

In the Brazi record the GS-1 cooling was primarily characterised by high relative abundance of *M. insignilobus*-type (Figure 4), which occurred only in low abundance previously and reached its maximum abundance in this phase. Since it is possible that this taxon includes several morphologically indistinguishable chironomid species in the training set, the estimated temperature optimum of *M. insignilobus*-type may not reflect accurately the temperature optimum of the taxon in the fossil assemblage. This problem might limit the value of this taxon for our temperature reconstruction and may account for the relatively stability of the chironomid-inferred temperature estimate during the Younger Dryas, despite the marked change in the chironomid assemblage at this time.

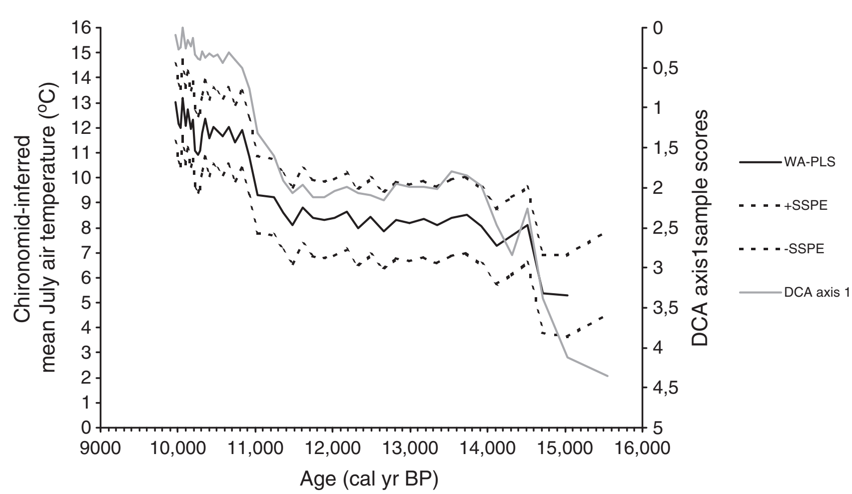

Figure 5. Chironomid-inferred mean July air temperatures at Lake Brazi (WA-PLS; solid line) plotted with sample-specific standard errors of prediction (SSPE; dashed lines) and first axis of a detrended correspondence analysis (DCA; gray line).

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A further distinct change in chironomid assemblages is apparent at *ca.* 11,200–10,800 cal yr BP, when a number of chironomid taxa colonized the lake (e.g., *P. austriacus*-type, *C. anthracinus*-type, *T. pallidicornis*-type2), after being absent or rare in earlier parts of the record. A high resolution diatom record (Buczkó et al., 2009) from the same sediment sequence suggested lake water acidification around 10,300 cal yr BP. Both *Chironomus* and *Psectrocladius* have been shown to tolerate low pH (Henrikson et al., 1982; Brodin and Gransberg, 1993), so this may also point to more acidic conditions in the lake during this interval. At *ca.* 10,200 cal yr BP, another major change is apparent in the record with an abrupt increase of eurytopic *T. mendax*-type, which replaced the previously dominant taxa. Both of these shifts were associated with a distinct increase in chironomid-inferred temperatures (Figure 5).

Late glacial July temperature changes in a regional context

Our late glacial chironomid-based July temperature reconstruction from Lake Brazi provides an important addition to the available LG quantitative climate reconstructions from Europe. It is most likely representative for the South Carpathian Mountains and valid for the northeastern Balkan area as well, since modern climate studies indicate a strong similarity in the climatic trends of this wider region (Kern and László, 2010). The only other LG chironomid record from this region (Figure 1) was published by Stefanova et al. (2003) from the Pirin Mountains (Bulgaria). Although, this record extends back to the Younger Dryas, it has a lower taxonomic resolution than the record from Lake Brazi and a quantitative climate reconstruction was not attempted.

When compared to other European quantitative climate reconstructions and the NGRIP δ^{18}O curve from Greenland (Figure 6; Björck et al., 1998; Rasmussen et al., 2006), the Brazi July temperature record shows some similarities, but also some differences: the onsets of the Bølling/Allerød intrestade (GI-1) and the Preboreal are well marked, but the Younger Dryas (GS-1) is weakly expressed and there is a delay in Holocene warming until *ca.* 11,000 cal yr BP.

The first marked temperature change was observed at 14,700 cal yr BP, when mean July air temperature increased by about 2.8°C (from 5.2-5.3°C to 8.1°C). A similar temperature increase (~3°C) was found in several other reconstructions in the Alps (Figure 1), for example at the Trentino area, northern Italy (Heiri et al., 2007), in the Jura Mountains, France (Heiri and Millet, 2005), in the southwestern Alps, Italy (Larocque and Finsinger, 2008) and on the Swiss Plateau (Larocque-Tobler et al., 2010); as well as from east-central Europe (Renssen and Isarin, 2001).

During the Bølling/Allerød interstade (GI-1), July mean temperatures were around 8.1–8.7°C at Lake Brazi. Present-day temperature of the warmest month is 11°C in the Retezat Mountains at 1740 m a.s.l., which is 2.5–2.9°C higher than the reconstructed values in the GI-1 interstade. From the eastern Carpathians, Feurdean et al. (2008a) published summer temperature estimates around 16–17°C during GI-1, based on pollen records from two lakes at 730 and 790 m a.s.l. (Figure 1). Using these pollen-inferred July air temperatures from the eastern Carpathians and assuming a 0.55°C lapse rate per 100 m (Pop, 1988), this would result in mean July temperatures around 11–11.5°C at 1740 m a.s.l., at the elevation of Lake Brazi. However, these values are considerably higher by *ca.* 1.3–3.4°C than our chironomid-inferred temperatures during the GI-1 interstade. This discrepancy might be attributable to the bias of the pollen based paleoclimate reconstructions at mountain sites, where uphill transport of tree pollen (particularly thermophilous broadleaved trees, e.g. *Quercus* and *Ulmus*) can lead to higher reconstructed temperatures that pertain to lower altitudes (Ortu et al., 2006). Most chironomid-based temperature reconstructions of the LG in Europe were published from lower elevation sites (Figure 1). At Lago Piccolo di Avigliana in the southwestern Alps, chironomid inferred temperatures were around 17.5°C during the Allerød (365 m a.s.l.; Larocque and Finsinger, 2008); *ca.* 15.5°C at Egelsee, Swiss Plateau (770 m a.s.l.; Larocque-Tobler et al., 2010); *ca.* 16.5°C at Lake Lautrey, Jura Mts. (788 m a.s.l.; Peyron et al., 2005) and *ca.* 15.3°C at Lago di Lavarone, Trentino area (1100 m a.s.l.; Heiri et al., 2007). A recent study from the Swiss Central Alps (Ilyashuk et al., 2009) reported 10–11.7°C July air temperatures during the GI-1 interstade at even higher elevation (1865 m a.s.l.) and latitude (46°24′ N) than Lake Brazi (Figure 1). The most likely explanation for the lower reconstructed temperature values in the southern Carpathians is the more oceanic climate of this mountain range relative to the Central Alps. In the Retezat extensive glacial advance was recorded after the last glacial maximum (Reuther et al., 2007). These glaciers started to melt around 16,200 cal yr BP, but Reuther et al.'s study suggests that the highest peaks remained under ice cover until the early Holocene. This may have exerted a cooling effect during the summers of the Bølling/Allerød interstade.

Probably the most striking feature of our temperature reconstruction was the weak July temperature decline at the Bølling/Allerød interstade–Younger Dryas transition (GI-1/GS-1; *ca.* 12,860 cal yr BP). While in many European chironomid-based summer-temperature reconstructions a significant decrease is recorded at this transition and the NGRIP δ^{18}O record also suggests abrupt cooling over Greenland, this is not detectable at Lake Brazi on the basis of chironomids (Figure 6). In contrast to our results, the decline in chironomid-inferred July temperatures was 1.5–2°C in the Southern Alps (Heiri et al., 2007), in the Trentino area, Italy (Larocque and Finsinger, 2008) and at Egelsee, Switzerland (Larocque-Tobler et al., 2010). However, a more pronounced (about 3–4°C) decrease was inferred at Lake Lautrey, France (Peyron et al., 2005) and at Maloja Riegel, in Switzerland (Ilyashuk et al., 2009). At the same time, the southern Carpathians are located relatively far from the North Atlantic, and so the influence of the thermohaline circulation may not be as strong as at sites in northern and western Europe. Based on model simulation, Renssen and Isarin (2001) also inferred weaker intensity of cooling (~2°C) in the southern Carpathian region during the GS-1 cooling. A late glacial vegetation reconstruction at Lake Brazi suggests conspicuous cooling and decreasing moisture availability during the GS-1 stade, which manifested in a rapid decrease in tree and shrub cover in the subalpine belt (mainly *P. mugo* decreased) and an increase in steppe-tundra (Figure 6; Magyari et al., 2009b). However, analysis of LG treelines (Magyari et al., 2009b) suggests that Lake Brazi remained within the treeline ecotone during the Younger Dryas, which could probably locally moderate cooling (Figure 6).

On the same sediment sequence, fine-resolution diatom analyses have also been made (Buczkó et al., 2009) and suggested that during the GS-1 winter ice-cover season may have been prolonged. These inferences were based on the rapid spread of a slightly acidophilous diatom (*Stauroforma exiguiformis* (Lange-Bertalot) Flower) at 12,800 cal yr BP. This species proliferates in arctic lakes oversaturated with CO_2 under thick and long-lasting ice cover.

Taken together, these results suggest that in the southern Carpathians the GS-1 cooling was mainly determined by winter cooling and seasonality change resulting in shortening of the growing season, while summer mean temperatures were less affected. However, considering the sample-specific prediction error of *ca.* 1.5°C for inferences based on the Younger Dryas samples, a moderate cooling in summer temperature during this episode may not have been registered in the reconstruction.

The beginning of the early Holocene (*ca.* 11,500 cal yr BP) was well-marked in the Lake Brazi chironomid record. July temperatures increased in two steps, the first increase was detected at *ca.* 11,500 cal yr BP when summer temperatures increased from 8.8°C to 9.2°C by 11,240 cal yr BP, and a further ~2.7°C increase was observed by 10,830 cal yr BP, when July mean temperatures rose to 11.9°C. Similarly, a two-step temperature increase at the Younger Dryas/early Holocene transition was described by Brooks and Birks (2000) at Kråkenes Lake, western Norway (Figure 1). On the whole, the amplitude of the temperature increase at

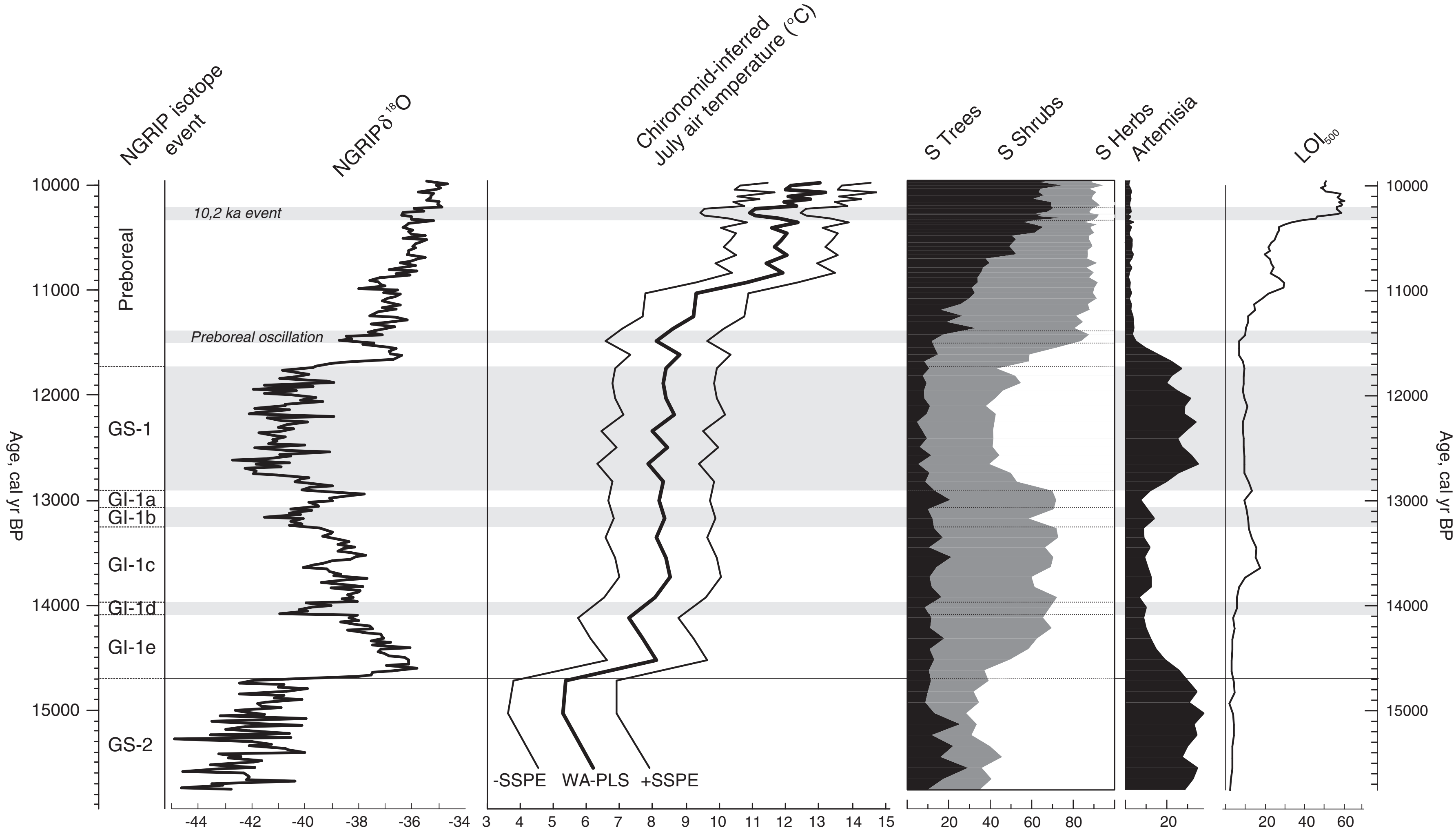

Figure 6. Chironomid-inferred temperature estimates (WA-PLS) and sample-specific standard errors of prediction (SSPE); relative abundance of selected pollen types (Magyari et al., 2009b) and loss on ignition (LOI) values from Lake Brazi compared with the NGRIP $\delta^{18}O$ record (Rasmussen et al., 2006). Gray bands correspond to cold events recorded in the NGRIP ice core.

Lake Brazi (~3.8°C) was similar to the one recorded at Maloja Riegel, central Swiss Alps, where Ilyashuk et al. (2009) found about a 4°C increase at the onset of the early Holocene. However, whereas the temperature increase in the Maloja Riegel record took place abruptly at the Younger Dryas to Holocene transition, the most significant warming in the Lake Brazi record clearly took place during the early Holocene (*ca.* 11,500–11,000 cal yr BP). Smaller increases in July air temperature (1.5–3°C), though again restricted to the Younger Dryas-Holocene transition, were inferred in northern Italy (Heiri et al., 2007; Larocque and Finsinger, 2008), in the Swiss Alps (Heiri et al., 2003) and in the Jura Mountain, France (Peyron et al., 2005).

During the early Holocene two short-lived cold periods were detected in the chironomid record of Lake Brazi. The first cold event between 11,480 and 11,390 cal yr BP agrees well with the Preboreal oscillation (e.g., Lotter et al., 1992). This short cooling showed only a slight decrease in summer air temperatures of 0.7°C (from 8.8°C to 8.1°C) at Lake Brazi similarly to other European temperature reconstructions, where a cooling of 0.5–3.5°C was described (e.g., Brooks and Birks, 2001; Peyron et al., 2005; Ilyashuk et al., 2009). The other short cooling event in our record dates between 10,350–10,190 cal yr BP. A similar short-term cooling was also reported from other parts of the Carpathian Mountains (between 10,100–10,500 cal yr BP; e.g., Tămaş et al., 2005; Feurdean et al., 2008b). This short-term cooling has also been detected in Western Europe (e.g., Heiri et al., 2004; Lang et al., 2010) and in the Greenland ice cores (Björck et al., 2001). Based on chironomid-inferred July air temperatures, minimum summer temperatures (10.9°C) were attained at *ca.* 10,250 cal yr BP, and the amplitude of the cooling was about 1°C. Biotic responses to this short-term cooling were also recorded by other proxies in Lake Brazi. For example, pollen influxes of major broadleaved taxa, *Corylus*, *Ulmus*, *Fraxinus* and *Quercus* decreased abruptly for 200 years and *Larix decidua* disappeared from the lakeshore. In addition, diatoms and Cladocera suggest a shift towards more acidic lake water and decreasing water depth around 10,300 cal yr BP (Buczkó et al., 2009; Magyari et al., 2009b).

Chironomid-based mean summer air temperatures started to increase again after the cold event between 10,350-10,190 cal yr BP and reached 13.2°C by 9970 cal yr BP. The temperature value during the early Holocene is about 2.2°C higher than the present-day July temperatures at 1740 m elevation in the Retezat Mountains.

Conclusions

We used the merged Norwegian–Swiss chironomid transfer function to reconstruct summer air temperatures during the late glacial and early Holocene (between *ca.* 15,700 and 10,000 cal yr BP) at Lake Brazi, in the southern Carpathian Mountains. Our chironomid-based temperature reconstruction indicates relatively cool July air temperatures of 5.2–5.3°C during the Oldest Dryas (GS-2), followed by an abrupt temperature increase to 8.1–8.7°C at the onset of the Bølling (GI-1), while only weak cooling during the Younger Dryas (GS-1) was observed. Later on, during the early Holocene, summer temperature increased in two steps and reached the level of 12.0–13.3°C by *ca.* 10,190 cal yr BP. Short term temperature decreases similar in age to cooling events documented in other parts of Europe and in the Greenland ice core oxygen isotope records are apparent in the Lake Brazi record. During the first event, most likely equivalent to the Preboreal oscillation (*ca.* 11,480–11,390 cal yr BP), reconstructed summer temperatures decreased slightly (0.7°C), while during the second cold event, between 10,350 and 10,190 cal yr BP, chironomid-inferred temperatures cooled by 1°C. Our study shows that during GS-1 there was a conspicuous change in the chironomid fauna, as well as in the local and regional terrestrial vegetation (Magyari et al., 2009b) and in the diatom flora (Buczkó et al., 2009), but summer temperatures remained relatively stable during the period. Other components of the climate, such as shifts in seasonality resulting in a shortening of the growing season, decline in winter temperatures and a fall in effective rainfall, probably explain the observed changes in the biotic proxies. Since July mean temperatures probably did not change significantly during GS-1 this suggests spring or autumn temperatures were cooler at Lake Brazi at this time.

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