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Quantitative reconstruction of climate variability during the Eemian (Merkinė) and Weichselian (Nemunas) in Lithuania

Vaida Šeirienė [a,*], Norbert Kühl [b], Dalia Kisielienė [a]

[a] Nature Research Centre, Institute of Geology and Geography, T. Ševčenkos 13, 03223 Vilnius, Lithuania
[b] Steinmann-Institute of Geology, Mineralogy and Paleontology, University of Bonn, Nussallee 8, 53115 Bonn, Germany

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ABSTRACT

Little is known concerning climate changes in the Eastern Baltic region during the last interglacial–glacial cycle and in particular, climate changes during the Weichselian. In this study, a quantitative reconstruction of the mean January and July temperature for the Medininkai-117 site in Lithuania is presented. The reconstruction is based on pollen and plant macrofossils from this site, which reveal that the vegetation was characteristic of many northern Europe sites during the Eemian and Early Weichselian. Gradual evolution of the vegetation suggests that relatively uniform climate conditions existed during the Eemian. Our reconstructions support the view of a relatively stable Eemian, with short cooling phases of low amplitude. A strong increase in temperature was apparent during the beginning of the interglacial and decrease during the transition to the Weichselian. Reconstructed July temperatures of the Eemian interglacial were approximately 2 °C higher than today (18.5 °C; today: 16.2 °C) and were similar to today for January (−5.2 °C; today: −5.1 °C). July temperatures during the Early Weichselian were only ~2°C lower than during the Eemian, whereas the January temperatures gradually decreased. Winter temperatures were relatively high (above −10 °C) during the Early Weichselian.

Introduction

Investigations of the Eemian interglacial period are of special interest for paleoclimatologists, because it is the most recent complete warm period and presents vegetation and climate changes that are uninfluenced by human activity. Therefore, this interglaciation plays a substantial role in better understanding and modelling future climate changes during the current warm stage—the Holocene. The transition from the interglacial to the glacial period and several distinct climatic events characterize the Weichselian period.

During the last decades different views of the climatic conditions of the Eemian and Early Weichselian emerged. Generally, the Eemian interglacial has been considered a period of relatively stable climate (Boettger et al., 2000; De Beaulieu and Reille, 1989, 1992; Guiot et al., 1992; Mamakowa, 1989; Pons et al., 1992; Tzedakis, 1993). The identification of substantial climate fluctuations from the oxygen isotope data in GRIP ice -core records (Dansgaard et al., 1993) directed the discussion to possible climate instability (e.g., Cheddadi et al., 1998; Field et al., 1994; Rousseau et al., 2007; Seelos and Sirocko, 2007). The consensus currently focuses on the relatively stable nature of the Eemian climate and also on the presence of short and low -amplitude cooling intervals during this period (Müller et al., 2005). Discussion remains regarding 1) the presence of thermal-favoured episodes during the Early Eemian (Aalsbersberg and Litt, 1998; Cheddadi et al., 1998; Guiot, 1990; Kühl and Litt, 2003); 2) several thermal optimum periods (Klotz et al., 2003); 3) differences between present- day and Eemian climatic gradients over Europe (Aalsbersberg and Litt, 1998; Gebhardt et al., 2008, Kaspar et al., 2005; Velichko et al., 2008; Zagwijn, 1996); 4) whether the Eemian interglacial was, at least in some regions, warmer than present (Aalsbersberg and Litt, 1998; Gebhardt et al., 2008; Velichko et al., 2008); and 5) continentality during the Early Weichselian with relatively high summer temperatures (Henriksen et al., 2008; Kühl et al., 2007; Valiranta et al., 2009).

Therefore, new results of climate evolution during this period from new sites and localities are still significant and will expand our knowledge. Because climate reconstructions from the Eastern Baltic region are nearly absent the purpose of our investigation is to provide a detailed quantitative reconstruction of the climate development of the Eemian and Early Weichselian from pollen and plant macrofossils from the Medininkai-117 site in Lithuania and compare it to other reconstructions.

Eemian (Merkinė) interglaciation sediments are widespread in Lithuania and have been recorded from approximately 40 sections mostly concentrated in the southeastern part of the country. Sometimes their thickness reaches approximately 40–60 m in the sections, which are not covered by the sediments of the last (Weichselian, Nemunas) glaciation. Vegetation succession and paleoclimate fluctuations that are recorded in pollen and plant macrofossil diagrams during the last interglacial have been described in many papers and summarized by Kondratienė

* Corresponding author at: Institute of Geology and Geography, Nature Research Centre, T. Ševčenkos str. 13, LT-03223, Lithuania. Fax: +370 2104695.
E-mail address: seiriene@geo.lt (V. Šeirienė).

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(1996). However, few attempts have been made to use numerical methods to obtain a more precise view of the climatic changes during this period. The first reconstruction, using probability theory proposed by Muratova et al. (1972), was performed by Kondratienė (1979) and based on pollen data. Climatic parameters were reconstructed only for the Eemian climatic optimum using data that were obtained from four sections. The reconstruction showed that the highest temperatures occurred during the beginning of the climatic optimum (M_{3a} zone), a decrease in temperature occurred during the M_{3b} zone and a repeated increase occurred at the end of climatic optimum (M_{3c} zone). During the last decade, the same method was used to process the pollen data of 34 Eemian sediment sections (Kondratienė and Šeirienė, 2000; Šeirienė and Kondratienė, 2005) and more detailed climate reconstructions were performed. The results obtained were similar to the previous ones. The methods appeared to be unsuitable for reconstructing the climate of treeless landscapes because it was impossible to obtain reliable parameters for the beginning and end of the interglacial and for the Weichselian glaciation. Other limitations of this method are that the growth probabilities were calculated only for a limited number of trees and only to the genus level. We know that the temperature and precipitation requirements of various species within the genus can be very different. In contrast, plant macro fossils can often be determined to species level and are more locally distributed; hence they can add important information about paleoclimate conditions (Birks and Birks, 2000).

Consequently, our recent study includes plant macro fossils and pollen and assesses climatic fluctuations by transferring the botanical data into quantitative climate information in a probabilistic manner which uses presence and quantifies uncertainty. For this approach, the Medininkai-117 section – one of the most complete late Pleistocene sediment sequences in Lithuania covering the time interval of the Eemian (Merkinė) interglacial to the Early-Middle Weichselian (Nemunas) – was chosen. The section was analysed for pollen and also plant macrofossil.

Study site and data

Study site

The Medininkai-117 borehole is in eastern Lithuania, 30 km south-east of Vilnius and 2.4 km north-west of Medininkai, in the central part of the Medininkai highland at 54°3′N and 25°7′E (Fig. 1). The modern January temperature at this site is −5.1 °C and the modern July temperature is 16.2 °C, with annual precipitation 675 mm. The site is a small paleolacustrine kettlehole filled with sediments. It is in the area outside the maximum limit of the Late Weichselian ice- sheet advance and presents a continuous sediment record spanning the entire Eemian (Merkinė) interglacial, Weichselian (Nemunas) glaciation and Holocene. Continuous sedimentation during these periods allows reconstructions

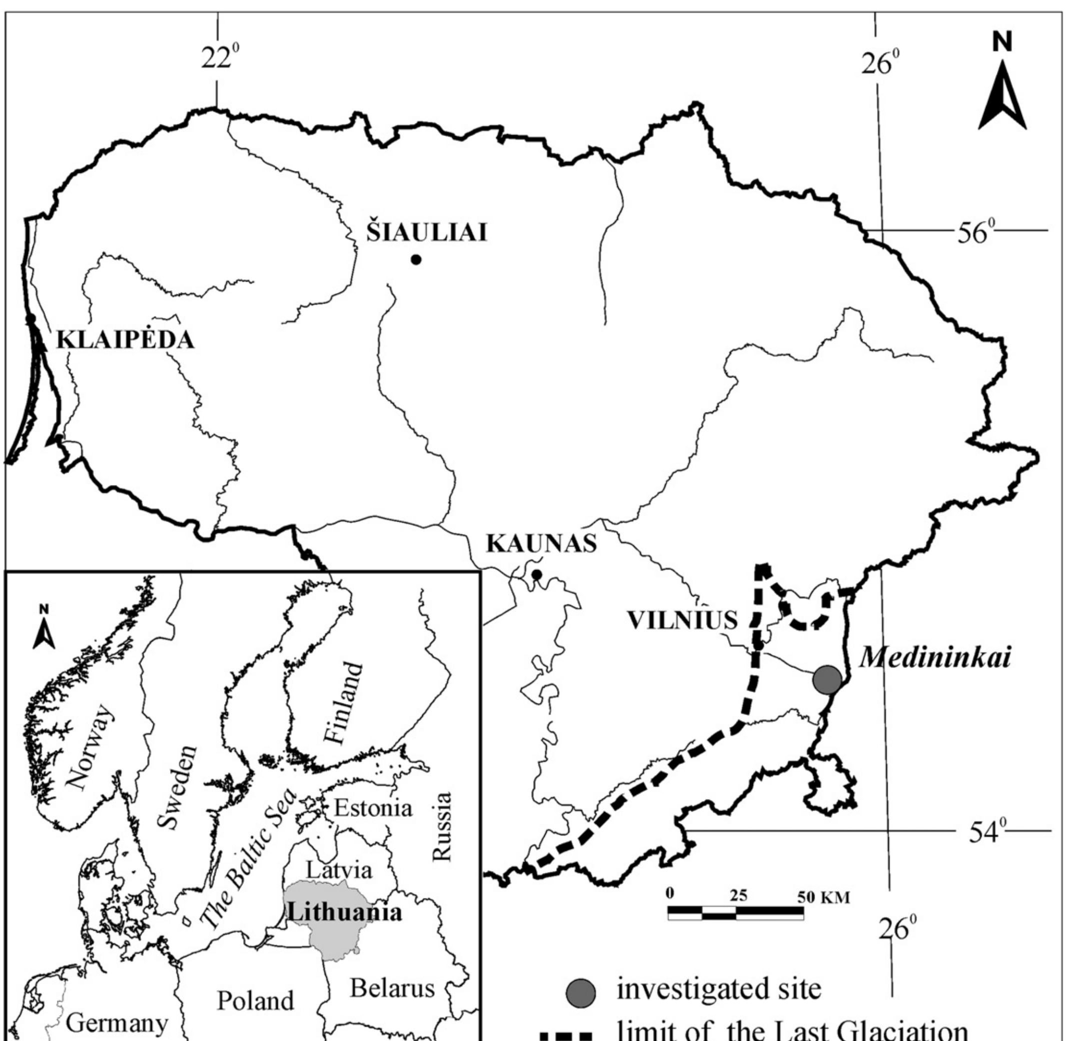

Fig. 1. Location of the site Medininkai-117 for which climate during the Eemian and Early Weichselian is discussed.

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of the climatic fluctuations not only for the Eemian interglacial but also for the Weichselian glaciation. The total thickness of the Upper Pleistocene and Holocene sediments in the section is 9.8 m and consists of silt, gyttja and peat (Table 1). These sediments are lying on top of Middle Pleistocene grey silt (9.8–10.2 m) and yellowish-brown till. The 20 cm peat layer underlying the silt is of Eemian interglacial age and most likely indicates the thermokarst transformations of the lake basin at the beginning of the interglacial.

The Medininkai site was discovered in 1977 during engineering-geological works in the area. Later, during the geological mapping of the area at a scale of 1:50,000 (1986–1991) the sediments of the Eemian and Weichselian paleobasins were studied in several boreholes. The investigations show that the Eemian (Merkinė) sediments were widely distributed in the Medininkai region (Kisielienė, 1999; Kondratienė, 1996; Kondratienė and Vonsavičiutė, 1986; Kondratienė et al., 1986; Satkūnas and Kondratienė, 1998; Satkūnas et al., 2003). The composition of Eemian deposits detected at other sites of the Medininkai highland is rather similar to those of borehole 117. It has been established that sedimentation occurred in separate paleolakes, scattered in the glacial relief of Saalian (Medininkai). There are no sites on the Medininkai highland where the Eemian deposits are overlain by Weichselian tills. This indicates that the Medininkai highland was not covered by an ice sheet during the Weichselian ice age.

The stratigraphic subdivision of the Medininkai-117 section is based on paleobotanical data. Correlations to other records can easily be made because of a marked uniformity of vegetational development across much of northern Europe during the Eemian. One sample (seed of *Larix* sp.) from 4.0 to 4.5 m was dated by ^{14}C in the Poznan Radiocarbon Laboratory, Poland, and gives an age of 37,000 ± 1000 ^{14}C yr BP (Poz-45736).

Pollen data

The interval 9.6–7.3 m corresponds to the M_1–M_5 local pollen zones (LPAZ) that are typical for the Eemian (Merkinė) Interglacial (Fig. 2) and it correlates well with analogous sections in Western Europe and neighbouring countries (Behre, 1989; Kalnina, 2001; Liivrand, 1991; Mamakowa, 1989; Zagwijn, 1961). Pollen analysis of the section was performed by O. Kondratienė (1996). The pollen diagram of the section shows a vegetation succession that was recorded from many Eemian (Merkinė) interglacial records and can be subdivided into seven pollen assemblage zones (Fig. 2). The beginning of the interglacial is indicated by the spread of *Pinus* and *Betula* forests (M_1) that later were transformed to more dense mixed forests (M_2) as shown by an increase in the types of tree pollen, including broad-leaved *Quercus* and *Ulmus*. The climatic optimum of the interglacial (M_3) can be subdivided into three subzones: M_{3a}—*Quercus-Ulmus*, M_{3b}—*Tilia* and M_{3c}—*Carpinus*. The first among the broad-leaved trees that appeared and spread were *Quercus* and *Ulmus* (M_{3a}). At the beginning they comprised mixed forests with conifers, mostly *Pinus*. Later, uniform forests of broad-leaved trees, including *Tilia*, appeared and spread much later than *Quercus* (M_{3b}). In the forests of south-eastern Lithuania, *Tilia* was most likely dominant (up to 70%). The *Corylus* underwood began forming during the maximum spread of *Quercus*. The maximum spread of the *Corylus* pollen was simultaneous to that of the *Tilia* and *Quercus* pollen. *Carpinus* appeared in the forests only in the second half of the climatic optimum (M_{3c}). After the climatic optimum *Picea* forests occupied the territory (M_4) and then they declined and were replaced by pine (M_5).

Table 1
Lithological description of the section Medininkai-117.

Depth (m)	Lithology
0.0–0.1	Top soil
0.1–2.1	Black–grey well decomposed peat with wood remains
2.1–2.6	Yellowish grey sandy silt
2.6–3.3	Dark greenish grey clayey silt
3.3–5.3	Black–grey massive sandy gyttja
5.3–5.8	Black–dark brown massive peat with mineral matter, wood remains and admixture of seeds
5.8–7.3	Greenish grey gyttja, from sandy to clayey
7.3–9.6	Greenish brown sandy gyttja, from 8.3 m with black gyttja blobs
9.6–9.8	Black–dark brown, massive, peat with mineral matter
9.8–10	Yellowish grey silt
10–14.2	Bluish grey, massive till with gravel and pebble

The disappearance of broad-leaved trees, deforestation of the area and the appearance of subarctic flora distinctly indicate the beginning of Weichselian (Nemunas) climate deterioration. The first stadial of the Weichselian covers 7.3–6.4 m *Betula* pollen increases to 30% in the upper part of this interval and the amount of herbaceous pollen is high. The macrofossil remains of *Selaginella selaginoides* and *Batrachium* are characteristic as well. The same vegetation changes were registered during Nemunas 1a (Nm_{1a}; Herning) stadial in the borehole Medininkai 117 P (Satkūnas et al., 2003), which is located 80 m north of the investigated section. The interval 6.4–5.8 m probably represents the Jonionys 1 interstadial (J_1; Brørup), because the number of herb pollen decreases, *Betula* decreases and *Pinus* pollen increases. It is proved by the presence of *Larix* pollen which is characteristic for Weichselian interstadials in Europe (Caspers and Freund, 2001; Satkūnas et al., 2003). The next interval (5.8–5.3 m) is characterized by a significant decrease in pollen concentration and increase in *Betula* pollen and *Batrachium* macrofossils. It is interpreted as being equivalent to Nemunas 1 b (Nm_{1b}; Rederstall) stadial. Sediment sequence between 5.3 and 4.8 m is characterized by rise in *Pinus*, *Picea* and *Larix* pollen. Findings of thermophilous macrofossils of *Najas marina* L. and *Ceratophyllum demersum* have been noted. These types of vegetation changes are typical for Jonionys 2 (J_2; Odderade) interstadial (Satkūnas et al., 2003).

The sediment section from 4.8 to 1.8 m could be attributed to Middle and Upper Weichselian (Nemunas); however, more detailed stratigraphical subdivision of the sediments is unclear and needs more absolute dates. *Corylus*, *Ulmus*, *Quercus*, *Tilia* and *Picea* pollen registered at the 3.6–1.8 m depth regarded as redeposited as the pollen grains are often badly preserved and the numerous old sporomorphs appeared at the same level.

The upper part of the section (0.5–1.8 m) accumulated during the Holocene. The concentration of pollen noticeably increased here, as well as the number of trees and thermophilous species.

Plant macrofossil data

Plant macrofossils in the section from a depth of 4.0–9.8 m were studied by D. Riškienė and D. Kisielienė (Kisielienė, 1999). Seventy-six taxa of fossil flora were indentified. These remains were collected from a small amount of material (drill core) and each interval that was analysed covered approximately 20–40 cm. Samples that covered two adjacent pollen zones were excluded from calculations. Two floristic complexes were distinguished in the studied sediments: lower (6.95–9.8 m) and upper (4.0–6.95 m). The first is from the Eemian interglacial which is characterized by a typical interglacial complex with thermophilic plants such as *N. marina*, *C. demersum*, *Potamogeton nodosus*, *Aldrovanda vesiculosa* and *Brasenia holsatica*. The occurrence of the latter species (*B. holsatica*) is scanty in Lithuanian Eemian (Merkinė) deposits, whereas in Belarus, the Eemian sediments contain tens of thousands of these species. Possibly, the northern boundary of the *B. holsatica* distribution during the Eemian interglacial passes through the territory of Lithuania (Kisielienė, 1999; Velichkevich, 1982). Trees were represented by *Picea* sect. *Picea*, *Pinus* sp., *Alnus glutinosa* (L.) Gaertn., *Carpinus betulus* L. and *Betula* sect. Albae. The flora of the upper part of the section is a different type and contains fewer species. The large species diversity (14 species) of representatives of *Potamogeton* is peculiar. Some are present in the lower part of the section as well, but the number increases considerably. Additionally, new species, such as *P. alpinus*, *P. vaginatus* and *P. sukaczevii*, which are attributed to the group of mild climate and frost-resistant species

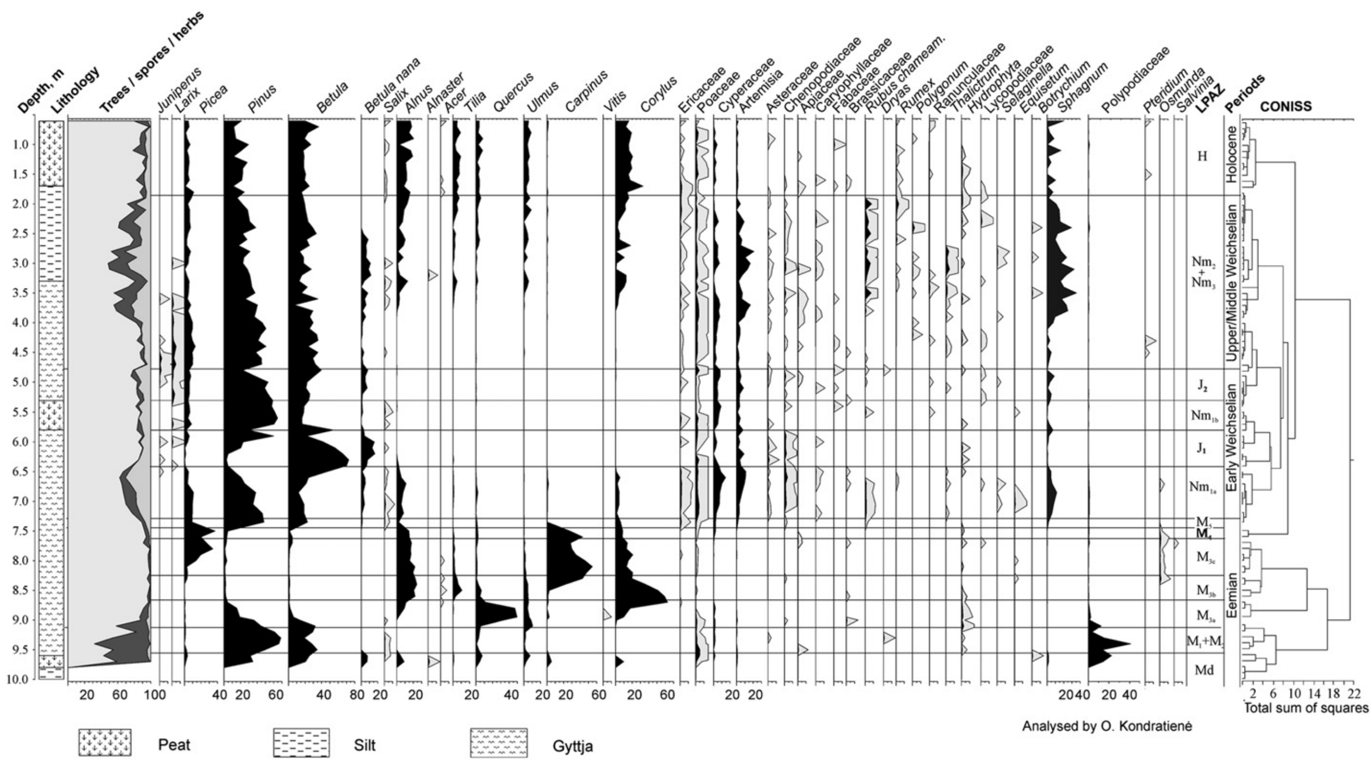

Fig. 2. Percentage pollen diagram of site Medininkai-117. Grey shade pattern represent ×10 exaggeration of base curves.

appear. The latter (*P. sukaczevii*) is rare in interglacial deposits, typical for the early glacial and very common in interstadials. In particular, numerous occurrences of this species are found in sediments that were formed during the early period of the last glaciation (Velichkevich and Granoszewski, 1996). Another species – *Ranunculus gmelini* – has also been noted from early glacial deposits.

Quantitative climate reconstruction method

The method applied here infers climatic information from the presence of individual taxa. Hence, it is an indicator taxa approach that estimates plant climate relationships and, subsequently combines the relationships of the different taxa to stabilize the reconstruction and narrow its uncertainty. In contrast to the classical indicator species method (Iversen, 1944), the approach used here estimates plant–climate relationships in a probabilistic way by probability density functions and combines them mathematically (Kühl et al., 2002). The result is the most probable climate with a quantification of uncertainty.

Data for estimating plant climate relationships come from digitized distribution maps (Meusel et al., 1964, 1978; Meusel and Jäger, 1992), that were calculated to a 0.5° × 0.5° spatial grid. This allows their combination with the CRU climate data (New et al., 2000) available at the same spatial resolution, from which the average values over the period 1961–1990, were used. To reconstruct the Eemian and the Holocene, the complete modern distribution areas were used to estimate plant–climate relationships. A modification (Kühl et al., 2007) was used for reconstructing Weichselian climate to incorporate the information that deciduous forest and warm steppe were absent at Medininkai during the Weichselian. For reconstructing Weichselian climate, plant–climate relationships were therefore estimated based on distribution areas that were reduced by areas with deciduous forest and warm steppe as well as those where permafrost conditions prevail today. Including this background information reduces the bias which could be introduced if taxa which are found in sediments of Weichselian age also occur in modern biomes which were definitely absent at Medininkai during the Weichselian.

Results

The results of the reconstructed climate show uniform climate with slight temperature fluctuations during the Eemian interglacial in Lithuania (Fig. 3). At the beginning of the interglacial an observable increase in both January and July temperatures is observed. The mean January temperature increased from −7 °C during the phase of mixed forests (M_{1+2}) to −4.5 °C during the *Quercus*–*Ulmus* (M_{3a}) phase and the mean July temperature increased from 16.5 °C to 18.5 °C, respectively (Fig. 3). The beginning of the climatic optimum, the *Quercus* and *Ulmus* phase (M_{3a}), was presumably the warmest period during the entire interglacial, and this is when the highest values of January and July temperatures are recorded. A slight decrease in temperature was observed during the successive phase (*Tilia;* M_{3b}). At that time, the mean January temperature decreased to −5.5 °C and the mean July temperature decreased to 17.5 °C. At the end of the climatic optimum during the *Carpinus* (M_{3c}) phase a marginal increase in temperature can be noted and here the January temperature reached −4.5 °C and the July temperature reached 17.8 °C. In the second half of the interglacial, the temperature gradually decreased. During the *Picea* (M_4) phase, the January temperature decreased to −7 °C and reached −9 °C during the *Pinus* (M_5) phase. The July temperature decreased from 16.5 °C to 16 °C during the *Picea* and *Pinus* phases, respectively.

The decrease in temperature at the end of interglacial is more pronounced for January (approximately 4 °C than July (approximately 1 °C. During the Herning stadial, the January temperature decreased from −8 °C to −9.5 °C whereas the July temperature remained high and showed marginal fluctuations, at approximately 16.5–16.8 °C. A slight increase of the July temperature (17 °C was noted during the Brørup interstadial, whereas the winter temperature remained stable (approximately −9 °C. A decrease in the January temperature began at the end of the Brørup and reached the −11 °C during the Rederstall stadial, whereas the summer temperature remained stable (~17 °C. The Odderade interstadial was the warmest during all the Weichselian, indicated by the January temperature increase to −8.5 °C and the July temperature range of 16.5–17.5 °C At the beginning of the Middle

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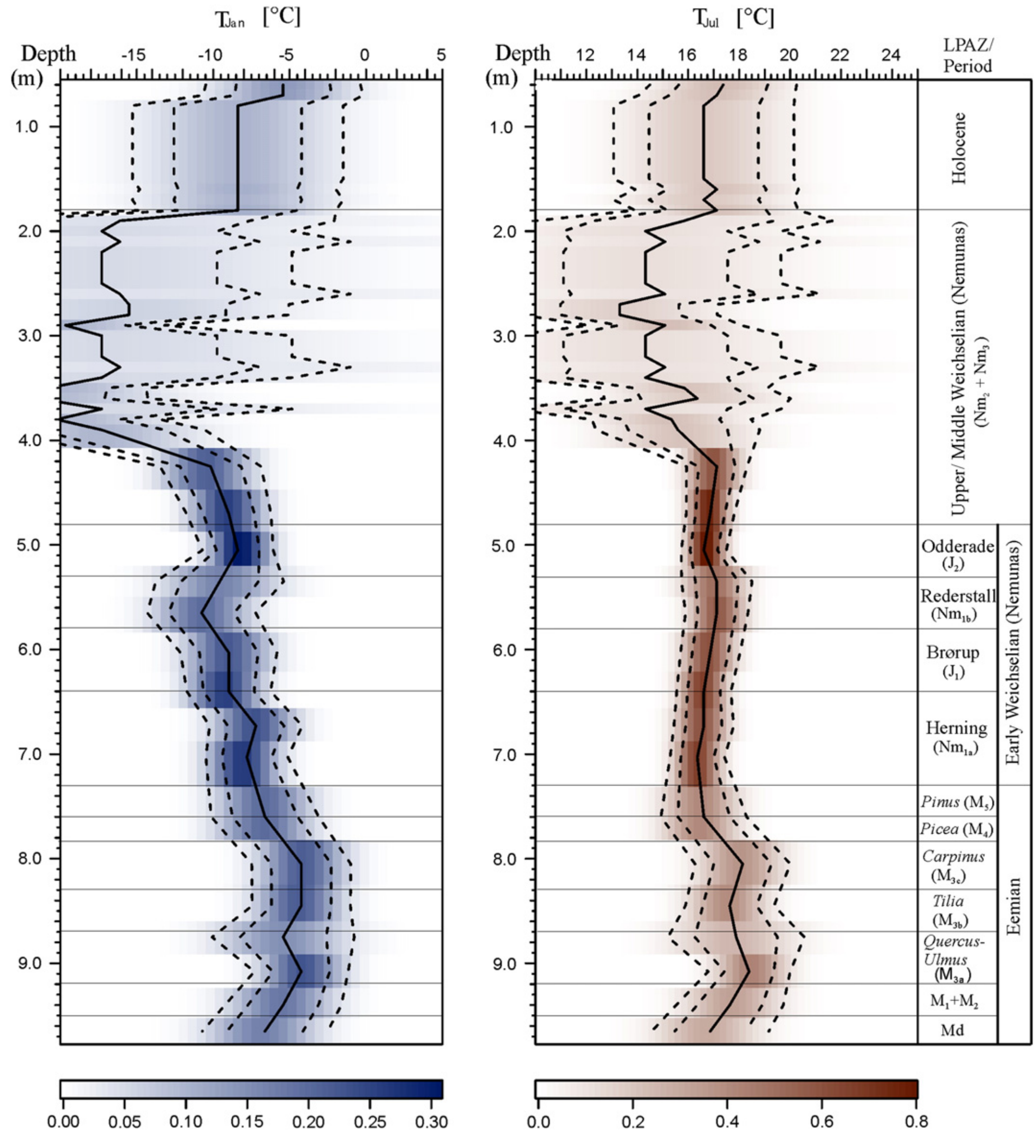

Fig. 3. Reconstruction of January and July temperatures during the Eemian and Weichselian at Medininkai-117. Intensity of colour relates to density of probability. The continuous line indicates the mean (most probable climate) and the dashed and dotted lines the single and double standard deviations, respectively.

Weichselian the decrease in the January temperature began, and after some time reached −20 °C The noticeable decrease in winter temperature is consistent with the decrease of summer temperature to 13–14.5 °C The uncertainty of the reconstruction is highest throughout the section during this period, because a maximum of four taxa contribute to the reconstruction. The reconstructed Holocene temperatures reach approximately 16.5 °C during the summer and −8.5 °C during the winter. The relatively high uncertainty during this period is a result of the use of 8–10 pollen taxa which originate from trees that exist within a broad climatic range. In contrast, the uncertainty range is relatively narrow for the reconstructions of the Eemian and early Weichselian, to which between 10 and 25 taxa (exception: 5.35 cm with 8 taxa) contribute. It must, however, be noted that taxa with a broad climatic range contribute only little to the most probable climate if taxa with a narrow range can be included in the reconstruction.

Discussion and conclusions

Our reconstruction indicates a low amplitude of climate variability during the last interglacial and a strong amplitude within the last glacial. Temperature changes are more pronounced during the winter and range from −8 to −4 °C during the Eemian and from −20 to −7.5 °C during the Early Weichselian to −20°C during its later part. Respectively, the summer temperatures fluctuated from 16.5 to 18.5 °C during the Eemian and from 17.5 to 13 °C during the Weichselian.

A winter temperature increase in the early part of the Eemian is observed in reconstructions from many sites in Europe (Zagwijn, 1996; Aalsbersberg and Litt, 1998; Cheddadi et al., 1998; Rioual et al., 2001; Kühl and Litt, 2003; Rylova et al., 2013) that were obtained using various reconstruction methods. The reconstructions made by Kühl and Litt (2003) at sites from Germany and France exhibit an increase of temperature of ~7–11 °C in January: from −13 to +2 °C at Bispingen, from −11 to 0 °C at Gröben and from −7 to 0 °C at La Grande Pile. The reconstructions made by Cheddadi et al. (1998) from five cores from eastern France and two cores from Poland using the "Best modern analogue" method show an increase up to 20 °C. The reconstructions from Belarus (Komotovo site) and Poland (Horoszki Duże site) do not show a remarkable increase and reach approximately 3 °C in January and 4–6 °C in July (Rylova et al., 2013). The later study is consistent with this one. However, it must be noted that the sediment of the beginning of the investigated section is compressed, preventing a detailed temporal analysis of gradual temperature change during this period.

The thermal optimum was registered during the first part of the interglacial in the *Quercus–Ulmus–Corylus* zone and the mean July temperature reached 18.5 °C at that time. The same temperature was observed in the reconstructions of Aalsbersberg and Litt (1998) from sites in Denmark, the Baltic Sea and the Gulf of Finland and this is consistent with the results of other investigations (Cheddadi et al., 1998; Kühl and Litt, 2003). The reconstructions from Belarus and Poland (Rylova et al., 2013) show the highest temperatures at the end of the first part of the thermal optimum, and they were approximately 19–23 °C in July. Overall, our reconstruction shows uniform climatic conditions during the thermal optimum and only a slight decrease of 1 °C in both July and January during immigration of *Tilia* in the mid-Eemian.

Our study is consistent with the temperature conditions for this period that have been reconstructed from the paleobotanical, coleopteran and periglacial data of 106 sites across north-western Europe by Aalsbersberg and Litt (1998) and with the spatial reconstructions of Gebhardt et al. (2008) using the probability density functions approach (pdf method). The reconstructions from Poland and Belarus (Granoszewski, 2003; Bińka et al., 2011; Rylova et al., 2013) do not show considerable climate fluctuations during this period. The reconstructed mean July temperatures of the climatic optimum appear ~2 °C higher than today and the same could be concluded regarding the January temperatures. Similarly, the July temperature could be 3 °C higher and the January temperature could be 5.5 °C higher compared to the present-day temperature of the territory of Belarus (Rylova et al., 2013). Coleoptera studies in England (Aalsbersberg and Litt, 1998) and pollen and plant macrofossil studies covering large parts of Europe (Kaspar et al., 2005; Zagwijn, 1996) indicate that the Eemian thermal optimum was warmer than the present day in the large part of Europe. During the last two Eemian phases July and January temperatures have dropped by several degrees and this is consistent with studies from the northwest and eastern Europe (Aalsbersberg and Litt, 1998; Kühl et al., 2007; Rylova et al., 2013).

The drop in temperature at the end of the interglacial is more pronounced in January (~4 °C than in July (~1 °C. However, the temperature decrease was much less than recorded at more western European sites for which a decrease of approximately −20 °C for January and 5 °C for July is reconstructed (Kühl et al., 2007; Brewer et al., 2008).

Quite high July temperatures ranging from 16 °C to 17.5 °C were recorded for the Early Weichselian period, which has also been observed in northern Fennoscandia (Valiranta et al., 2009). At Medininkai, no obvious temperature changes during stadials and interstadials were observed. Presumably this is related to concurrent orbital forcing and sustains the view that summer insolation was not much lower during the Early Weichselian than during the Last Interglacial (Helmens and Engels, 2010). This could mean that the strong decrease in winter temperature during the early Weichselian reconstructed for some Western Europe sites (Kühl et al., 2007; Brewer et al., 2008) was caused by feedback mechanisms which did affect Lithuania to a much lesser degree. January temperatures gradually decrease from −7 °C during the Herning stadial reaching −11 °C during the Rederstall stadial. The Rederstall stadial was the coolest period during the Early Weichselian. The presence of warm water diatom species such as *Aulacoseira granulata*, *Cymbella ehrenbergii*, *Stauroneis phoenicenteron* and *Anomoneoneis sphaerophora* during the Early Weichselian supports this assumption (Šeirienė and Grigienė, 2001). Nevertheless, the temperature appears to be relatively high for the Early Weichselian and implies non-glacial conditions. Similarly, the results from both electron spin resonance (ESR) and palynological analyses in the Northern Eurasia and Voka section at south-eastern coast of the Gulf of Finland suggest that interglacial climatic conditions may have persisted until the end of MIS 5a (Molodkov and Bolikhovskaya, 2010, 2011). This presumption is also consistent with recent data from the Netiesos section in southern Lithuania (Baltrūnas et al., 2013) indicating the warm character of MIS 5d. The newly studied section in northern Lithuania shows that this region was ice-free at least from 55 to 33 ka (Satkūnas et al., 2013). There is also evidence of a warmer-than-present climate during the Brørup interstadial obtained by plant macrofossils studies from the Sokli sediment sequence in Finnish Lapland (Valiranta et al., 2009), showing the July temperatures at least 3 °C higher than at present, and from northern Russia (Henriksen et al., 2008) where the Odderade interstadial appears to be as warm as an interglacial. Additionally, several recent detailed investigations that encompass sediments dated to the early MIS 3 reinforce the idea of ice-free conditions in central and northern Fennoscandia during this period (Lunkka et al., 2008; Alexanderson et al., 2010; Helmens and Engels, 2010; Wohlfarth, 2010; Möller et al., 2013). In this context, the reconstructed temperatures are plausible and contribute to providing a more complete picture of environmental changes during the Last Interglacial–Glacial cycle.

According to reconstructions made at other European sites the beginning of the Eemian suggests a southeast to northwest gradient for both the warmest and the coldest month. The second half of the interglacial is considered more oceanic than the early part (Aalsbersberg and Litt, 1998; Zagwijn, 1996). However, in Lithuania, summer temperatures fluctuate from 18.5 °C during the first part of interglacial and 17.8 °C during the second. Thus, these data are consistent with an 18 °C July isotherm over Denmark, the Baltic Sea and the Gulf of Finland according to Aalsbersberg and Litt (1998). Our reconstruction is also consistent with model simulations (Felis et al., 2004; Kaspar et al., 2005), which indicate higher than present Eemian temperatures by ~2 °C in Eastern Europe during the thermal optimum, supporting the view that orbitally induced changes of insolation were sufficient as the main factor forcing temperature fluctuations. Less pronounced temperature changes during the beginning and the end of interglacial are possibly related to the northeastern geographical position of Lithuania because the temperature gradient to the south is more pronounced. Reconstructed relatively warm Early Weichselian temperatures support the latest findings of ice-free and warm conditions in middle-eastern Fennoscandia.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.yqres.2014.04.004. These data include Google maps of the most important areas described in this article.

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