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Thermal gradients in Europe during the last glacial-interglacial transition

H. Renssen[1,3*], R.F.B. Isarin[2] & J. Vandenberghe[3]

[1] Institut d'Astronomie et de Géophysique Georges Lemaître, Université catholique de Louvain, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium.
[2] Archaeological Consultancy RAAP, Zeeburgerdijk 54, NL-1094 AE Amsterdam, The Netherlands; e-mail: r.isarin@raap.nl
[3] Netherlands Centre for Geo-ecological Research (ICG), Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands; e-mail: renh@geo.vu.nl
* corresponding author

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Abstract

Temperature profiles along east-west and north-south transects in Europe are presented for four time-slices covering the two most prominent warming phases of the last glacial-interglacial transition: Late Pleniglacial (LP), early Bølling (BL), Younger Dryas (YD), and Preboreal (PB). These temperature profiles are based on two methods: 1) simulation experiments with an atmospheric general circulation model, 2) reconstructions based on terrestrial geological and palaeoecological data. The profiles have The Netherlands as intersection point (52°N, 5°E). During the cold phases (LP and YD), the simulated and reconstructed temperature gradients are very steep in a north-south direction, ranging in January from –25°C in northern Europe (56-60°N) to at least 5°C near the Mediterranean, and in July from 0°C to 20°C. The east-west profiles along 52°N for LP and YD show that temperatures in Eastern Europe were similar to the Atlantic coast (i.e. between –15°C and –25°C). During the warm phases (BL and PB), the temperature regimes resembled present-day thermal conditions, although steeper north-south and east-west temperature gradients were present during BL and PB. The model simulations suggest that continental Europe was a few degrees warmer during PB and BL than today in July under influence of the relatively high summer insolation. Considering the change of climate through time, the profiles show that in The Netherlands the warming during the two transitions (LP-BL, YD-PB) was relatively small compared to regions to the West and North, whereas in Eastern and Southern Europe the temperature increase is even smaller. This reflects the dominant influence of latitudinal movements of the North Atlantic polar front and associated sea-ice margin.

Keywords: climate change, climate modelling, climate reconstruction, Europe, Late-Glacial, palaeotemperatures

Introduction

In Europe the last deglaciation period was characterised by rapid and drastic climate fluctuations. Two prominent warming phases clearly stand out: the Late Pleniglacial-Bølling (~14.7 cal ky BP) and Younger Dryas-Preboreal (~11.5 cal ky BP) transitions. High-resolution proxy records from the North Atlantic region have revealed that during the two shifts annual mean temperatures increased by more than 10°C in a few decades (e.g., Grootes et al., 1993; Taylor et al., 1993; Von Grafenstein et al., 1999). In recent years these two examples of climate change have received considerable attention, as they may hold clues to natural climatic behaviour under changing forcing conditions (Vandenberghe et al., 2001). We mapped the two transition phases in Europe by applying two independent techniques: 1) climate reconstruction based on terrestrial geological (e.g., periglacial phenomena) and palaeoecological (e.g., pollen) data and 2) simulation with numerical climate models (Renssen & Isarin, 2001).

The main results of the latter study may be summarized as follows. January temperatures in NW Europe increased by up to 20°C during both the 14.7 and 11.5 cal ky BP shifts. Summer conditions changed less abruptly, as the increase in July temperatures in NW Europe was estimated at 3 to 5°C. We inferred that the strong increases in January temperature were mainly caused by northward shifts of the North Atlantic polar front and the position of the winter sea-ice margin. In July, the temperature change during the climatic shifts was determined by a combination of the increase in summer insolation and the warming of the North Atlantic Ocean. In Scandinavia and Scotland the July temperatures were also controlled by the retreat of the ice sheets. Our inferences are in general agreement with other regional reconstructions (e.g., Coope et al., 1998).

In this paper we present temperature profiles along north-south and east-west transects in Europe (Fig. 1) based on the modelling results presented in Renssen and Isarin (2001). Four climatic phases are considered: Late Pleniglacial (~18-14.7 cal ky BP), early Bølling (14.7-14.0 cal ky BP), Younger Dryas (12.7-11.5 cal ky BP) and Preboreal (11.5-10.5 cal ky BP). In addition, we use temperature estimates reconstructed using multi-proxy data from Renssen and Isarin (2001) to verify the simulated gradients. The north-south transects are established along 5°E and extends from 60°N (southern Norway) to 40°N (Mediterranean Sea). Similarly, the east-west transects include temperatures from 40°E (western Russia) to 15°W (North Atlantic near Ireland) along 52°N. Consequently, the geographical position of The Netherlands (~5°E, ~52°N) is chosen as the intersection point of the two transects. Hence, using these gradients, we are able to compare the seasonal temperature regimes in The Netherlands with neighbouring regions through time.

Numerical climate model experiments

Climate model experiments were carried out with the ECHAM4-T42 atmospheric general circulation model of the Max-Planck-Institute for Meteorology in Hamburg. This global model with a horizontal resolution of ~2.8 x 2.8 degrees latitude-longitude simulates a modern climate that is in general agreement with present-day meteorological data (e.g., Roeckner et al., 1996). The ECHAM4-T42 model is described in detail in Roeckner et al. (1996) and DKRZ (1994). It should be noted that the model is designed for a sub-continental to global scale. Consequently, region-

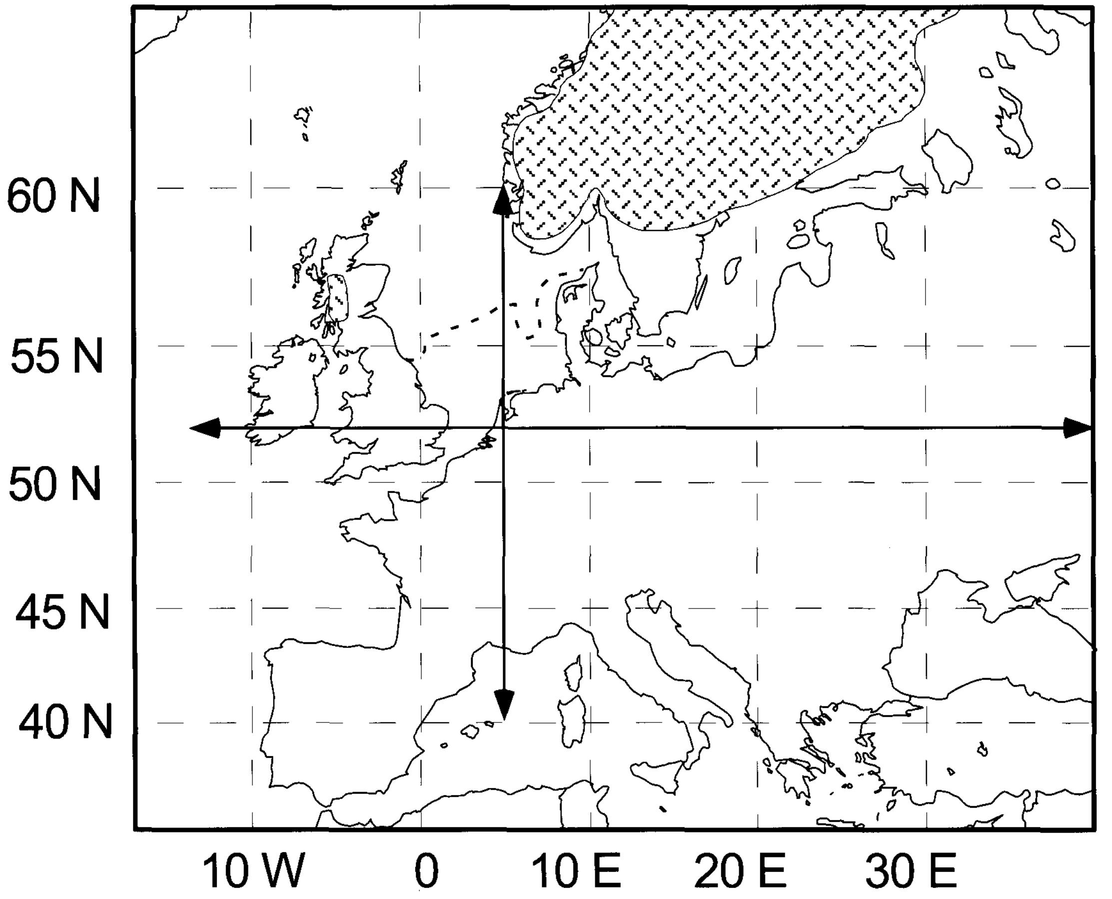

Fig. 1. Position of two transects presented in this study. Also included are the icesheet margins (hatched) and the North Sea coastline (broken line) at ~12 cal ky BP (Younger Dryas).

al climatic effects (due to, e.g., orography) are poorly represented.

Five equilibrium experiments were carried out; one control experiment with present-day boundary conditions and four palaeoclimate experiments in which boundary conditions were prescribed that characterise the four periods central in this study: Late Pleniglacial, early Bølling, Younger Dryas and Preboreal. The sets of boundary conditions have been described elsewhere (Renssen and Isarin, 2001) and are summarized in Table 1. Sea surface conditions for YD and BL are based on Koç et al. (1993), Sarnthein et al. (1995) and Schiller et al. (1997); those for LP on CLIMAP (1981). The ice sheet extent and topography are according to Peltier (1994), while insolation is prescribed following Berger (1978). The atmospheric concentrations of CO_2 (ppm), CH_4 (ppb) and N_2O (ppb) are based on Antarctic ice core analyses (Raynaud et al., 1993). Vegetation parameters (i.e. surface albedo, vegetation ratio, forest ratio, leaf area index and surface roughness length) are according to Claussen et al. (1994) and Adams (1997). In YD a simple permafrost parameterisation is included for regions with permafrost, consisting of two measures: 1) fixed frozen subsoil, 2) permanent high water table (see Renssen et al., 2000). In all palaeo-experiments the southern North Sea region (south of 55°N) is assumed to consist of land instead of sea, following global sea level reconstructions (e.g., Fairbanks, 1989).

Temperature reconstruction based on multi-proxy data

In Renssen and Isarin (2001), a reconstruction of the January and July temperature distribution in Europe was made for the four selected phases based on available multi-proxy data (cf. Huijzer and Isarin, 1997; Vandenberghe et al., 1998). These data were partly compiled from literature and partly derived from existing databases. The different types of proxy information include periglacial evidence, climate indicator plant species data and fossil beetle assemblages (Coleoptera). The existing databases and regional reconstructions that were used are the periglacial datasets of Isarin (1997) and Huijzer and Vandenberghe (1998), the temperature reconstructions of Zagwijn (1994) and Isarin and Bohncke (1999) and the Coleoptera data of Coope et al. (1998). In addition, 148 pollen diagrams were collected from literature or retrieved from the European Pollen Database, after which the climate indicator plant species technique was applied to infer past thermal conditions. It should be noted that the reconstructed winter temperatures for the warm phases (early Bølling and Preboreal) are based on a few data points only, making these estimates less reliable than others.

Results: temperature gradients in Europe

For each of the five experiments summarized in Table 1, seasonal (i.e. January and July) temperature gradients along north-south (along 5°E) and east-west (along 52°N) transects are calculated and plotted. In addition, temperatures based on multi-proxy data (derived from the maps of Renssen & Isarin, 2001) are also plotted for comparison. All presented temperatures have been converted to sea level, using a lapse rate of 6°C/km.

Table 1. Summary of experimental design ('ky' stands for cal ky BP).

Boundary conditions	Experiments				
	CTL modern control	PB Preboreal	YD Younger Dryas	BL early Bølling	LP Late Pleniglacial
Sea surface temperatures	0 ky	0 ky	North Atlantic cooling north of 30°N: progressive cooling towards −10°C at 60°N North Pacific cooling north of 40°N: -2°C	Nordic Seas cooling north of 60°N: 2 to 10°C rest as CTL	Glacial: global cooling
Sea-ice cover	0 ky	0 ky	North Atlantic limits: 55-60°N (winter) 65°N (summer)	Nordic Seas perennially ice covered	North Atlantic: 45°N (winter) 60°N (summer)
Ice sheets	0 ky	11 ky	12 ky	14 ky	15 ky
Insolation	0 ky	11 ky	12 ky	14.5 ky	15 ky
$CO_2/CH_4/N_2O$	353/1720/310	260/720/270	246/500/265	220/650/220	220/450/220
Vegetation parameters	0 ky	Preboreal	Younger Dryas	Bølling	Glacial
Land-sea distribution	0 ky	11 ky	12 ky	14 ky	15 ky

Simulated North-South transect along 5°E

January

In CTL (present-day climate) a moderate N-S gradient is present between 45 and 60°N, as the January temperatures remain in the range of 0 to 5°C throughout this zone (Fig. 2a). The gradient only becomes steeper near the Mediterranean Sea (i.e., south of 45°N), where values rise from 0 to 15°C in 5 degrees of latitude. A similar profile is present in the PB-experiment, although temperatures are a few degrees lower in PB compared to CTL over the continental interior.

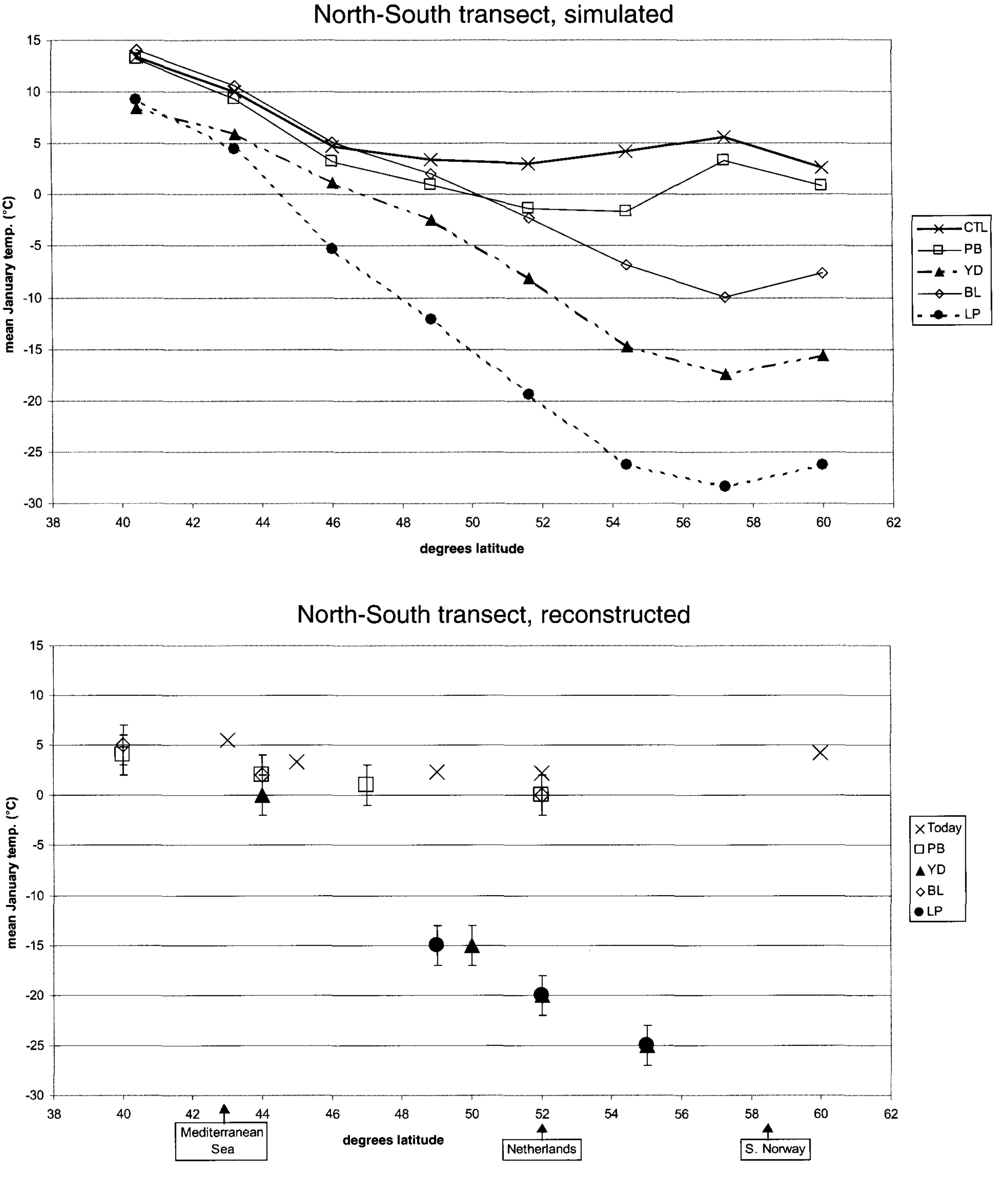

Fig. 2a-b. North-south mean January surface temperature profiles (°C) along 5°E, covering 60 to 40°N. 2a) Simulation results for five experiments: CTL (cross), PB (rectangle), YD (triangle), BL (diamond) and LP (circle), 2b) Reconstructed for Preboreal (rectangle), Younger Dryas (triangle), early Bølling (diamond) and Late Pleniglacial (circle). A rough estimate of uncertainty of 2°C is indicated (cf. Isarin and Bohncke, 1999). For reference, modern observed mean January temperatures (cross) are also plotted for some stations (mean for 1931-1960, data from Wallén, 1970; 1977).

In contrast, in the other experiments, rather steep N-S January profiles with comparable slopes are present in the northern section (between 45 and 60°N) in YD, BL and LP. Of course, the absolute values are quite different. For instance, January temperatures for BL are between –10 and –5°C in Northern Europe, whereas in LP these values are below –25°C. In addition, in the southern section, the slope of LP becomes much steeper than those ofYD and BL.

July

In the northern North Sea region, large differences in the slope of the N-S July temperature profile exist between the five experiments (i.e., 54 to 60°N, Fig. 3a).

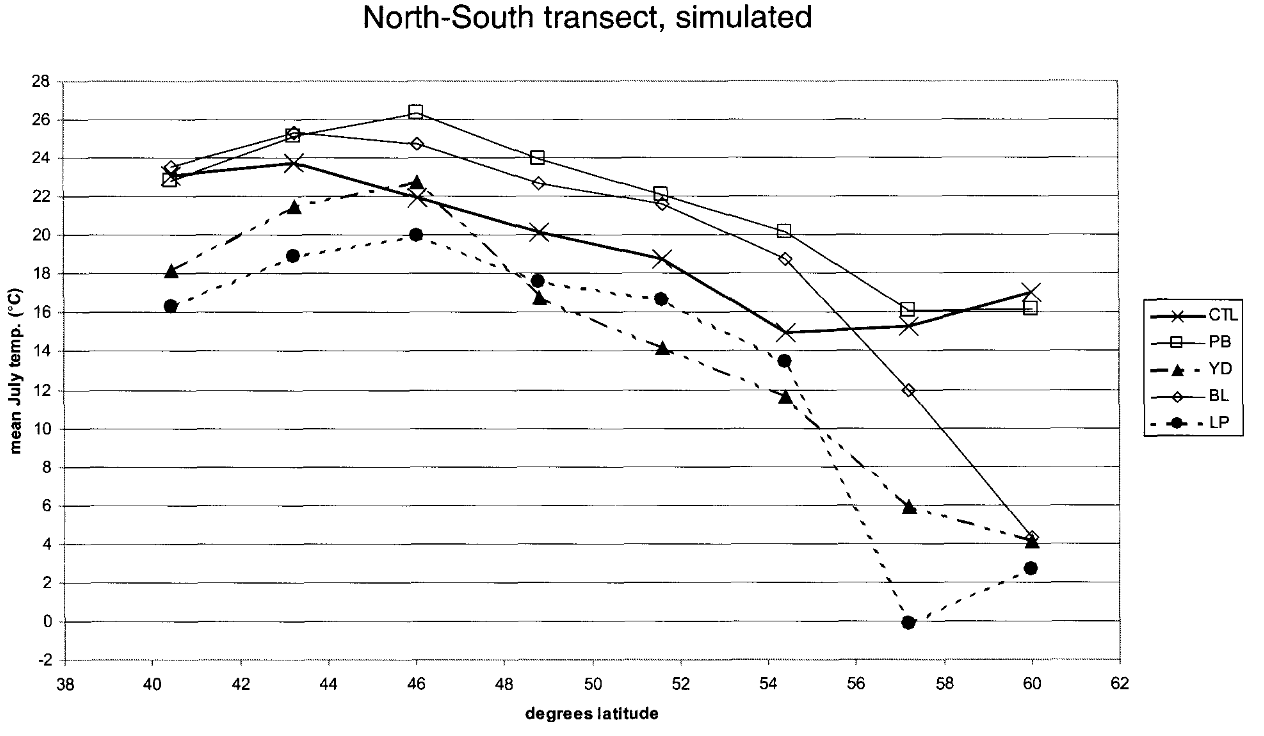

Fig. 3a. As Fig. 2a, but for July.

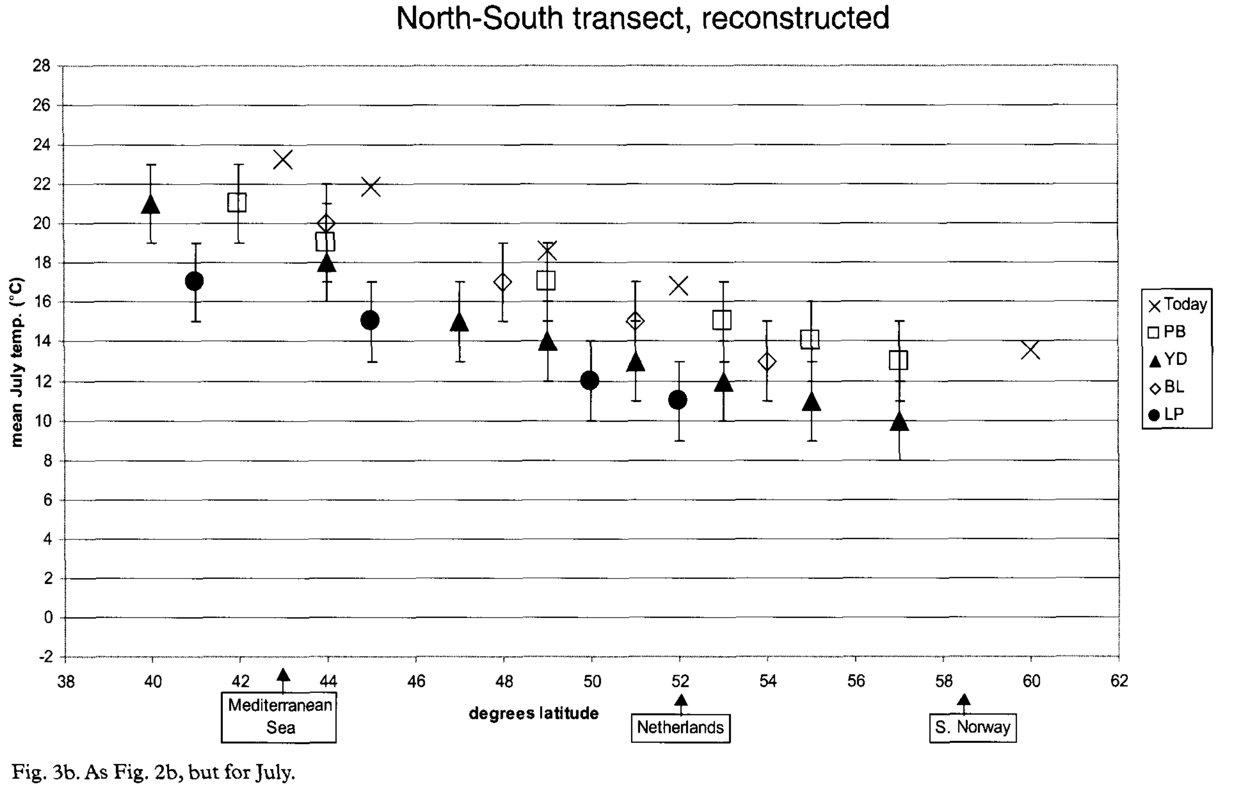

Fig. 3b. As Fig. 2b, but for July.

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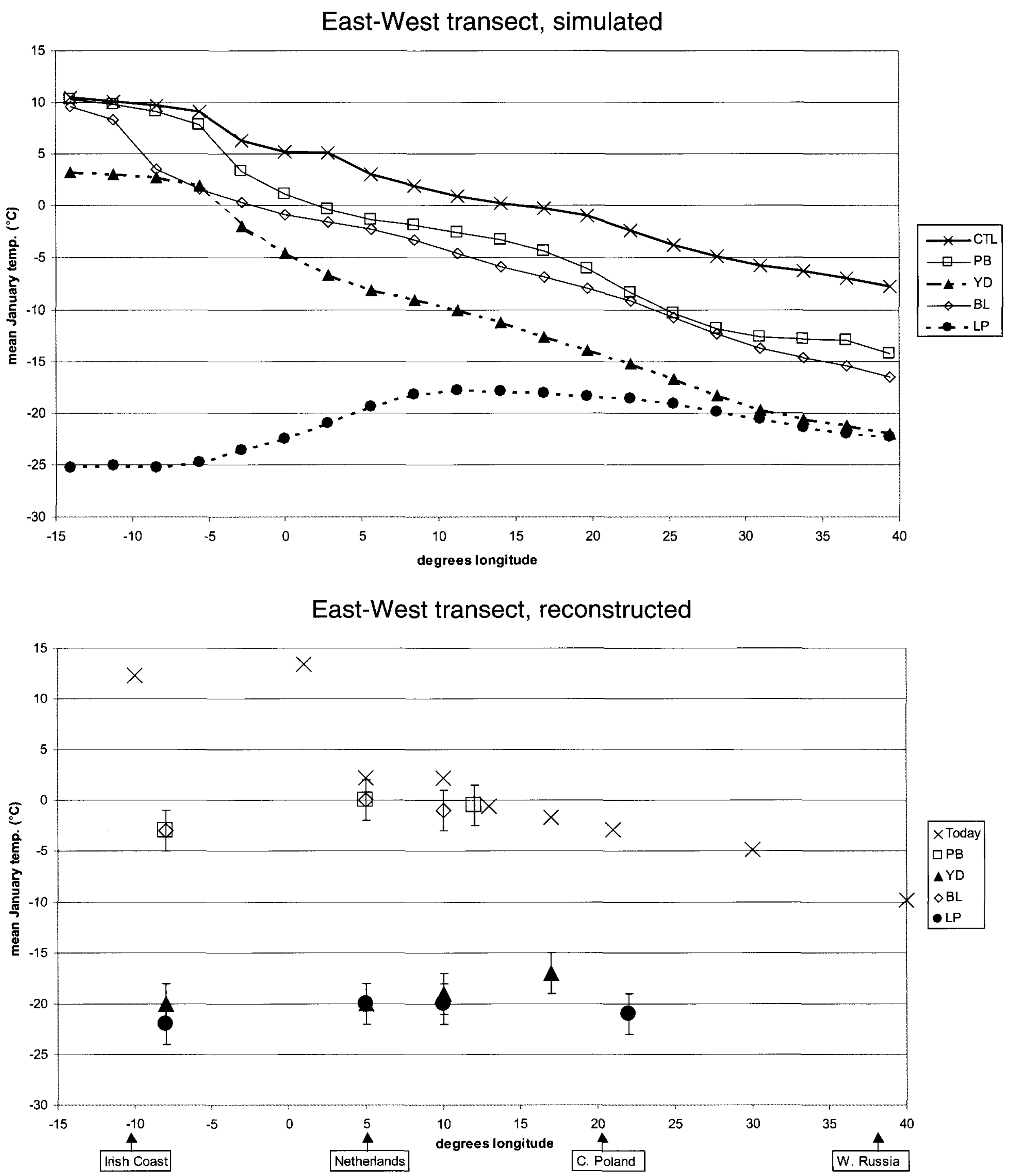

Fig. 4a-b: East-west mean January surface temperature profiles (°C) along 52°N, covering 40°E to 15°W. 4a) Simulation results for five experiments: CTL (cross), PB (rectangle), YD (triangle), BL (diamond) and LP (circle), 4b) Reconstructed for Preboreal (rectangle), Younger Dryas (triangle), early Bølling (diamond) and Late Pleniglacial (circle). For reference, modern observed mean January temperatures (cross) are also plotted for some stations (mean for 1931-1960, data from Wallén, 1970; 1977).

Here, the steepness of the slope increases in the order CTL, PB, YD, BL and LP. Compared to the 54-60°N trajectory, the temperature profiles are flattened south of 54°N, except for the gradient of CTL. Towards the Mediterranean Sea, all experiments show decreasing July temperatures.

Simulated East-West transect along 52°N

January

The January east-west transects for PB and BL are similar, as they both cover around 26°C between Russia (about -15°C at 40°E) and the Atlantic Ocean (+10°C at 15°W, Fig. 4a). This gradient is notably steeper than in the case of CTL, whereas the slope is comparable to that of YD profile, the latter extending from −22° C at 40°E to 3° C at 15°W. In contrast, January temperatures in LP do not increase from east to west and fall in the range of about −25 to −17° C throughout the profile, with a maximum between 5 and 20° E and decreasing values towards the North Atlantic coast.

July

Again, the gradients of PB and BL are comparable, with July temperatures ranging from 24° C at 40° E to

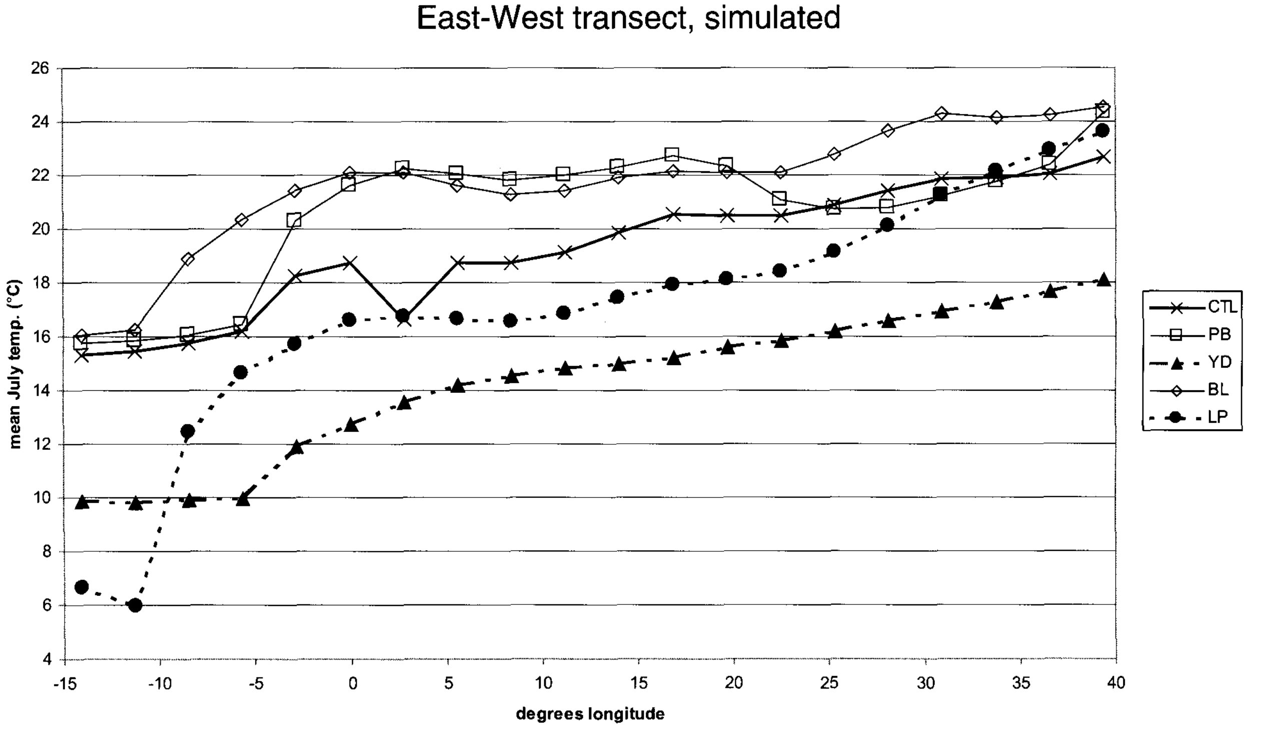

Fig. 5a. As Fig. 4a, but for July.

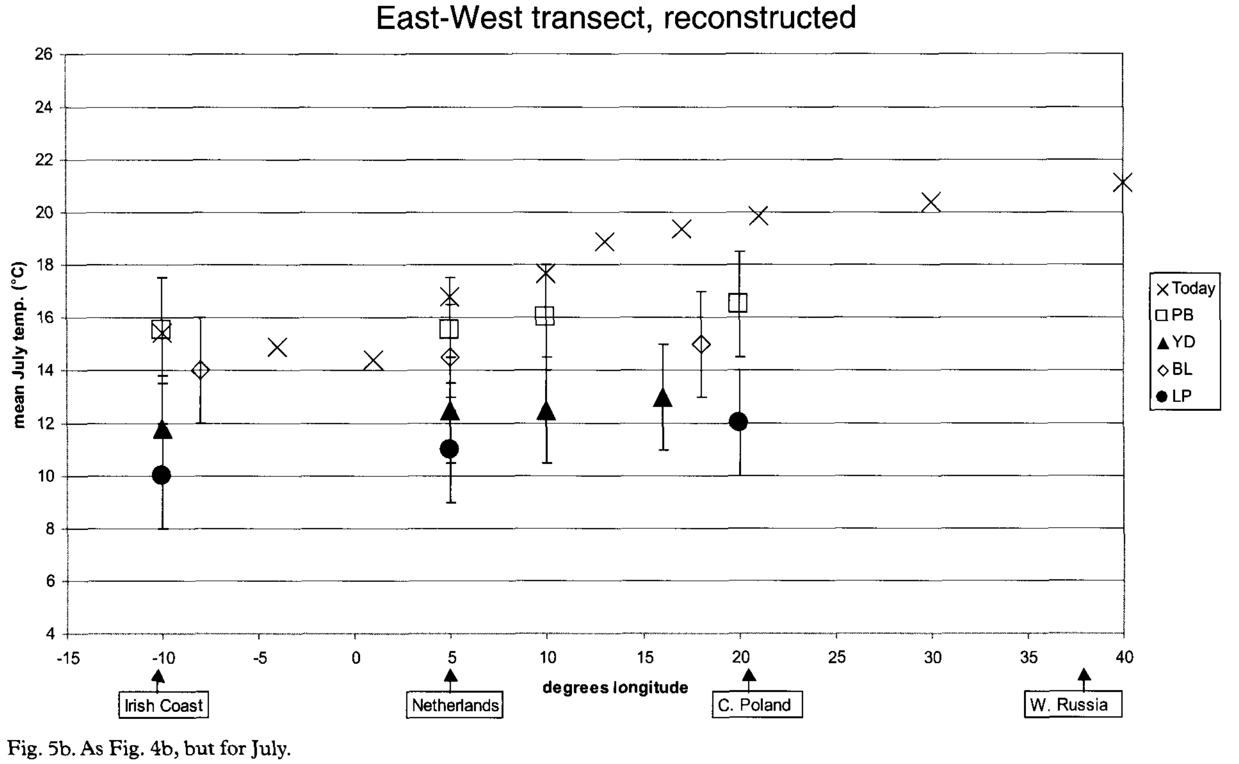

Fig. 5b. As Fig. 4b, but for July.

16° C at 15°W, implying a total range of 8° C (Fig. 5a). Compared to CTL, in PB and BL a rather steep temperature gradient is present near the Atlantic coast (between 0 and 15° W). The profile for YD covers also 8° C from 40° E to 15°W, but the July temperatures are much lower and vary from 18° C to 10° C. The LP east-west July gradient is twice as steep as the results of the other experiments, with comparable temperatures to PB and BL in Russia (i.e., 23° C), decreasing in western direction to 6° C over the Atlantic Ocean.

Effect of boundary conditions

January

The differences between the five January north-south gradients reflect mainly the prescribed changes in the Atlantic Ocean surface conditions (Fig. 2a). For instance, the comparable gradients in PB and CTL are associated with the assignment of identical sets of sea surface temperatures (SSTs), whereas the relatively low temperatures in northern Europe in BL are related to the strong ocean cooling prescribed in the Nordic Seas in this experiment. In YD and LP the winter sea-ice margins are defined at 55-60°N and 45°N, respectively. These are the latitudes where the January north-south profiles fall below –5° C. It means that LP is the only experiment in which the east-west transect is calculated at a latitude North of the prescribed winter sea-ice margin (Fig. 4a). This explains the different shape of the LP profile, with decreasing temperatures to the west instead of increasing values. Consequently, unlike the other experiments, in the LP-case the Atlantic Ocean is a source of cold air due to the intense cooling over the extended sea-ice cover (Renssen & Isarin, 2001).

The effect of changes in other boundary conditions on the January temperatures is smaller, but certainly not negligible. For example, the lower January temperatures in PB compared to CTL between 54 and 48°N (Fig. 2a) may be attributed to a combination of lower winter insolation values and a different land-sea configuration with the North Sea coast at 55-56°N instead of 52°N.

July

The July profiles for the continent show that temperatures were a few degrees higher in BL and PB compared to present-day values, which must have been caused by the relatively high insolation values, as other changed boundary conditions (i.e. ocean surface conditions, greenhouse gas concentrations and ice sheets) are expected to have caused a cooling effect compared to CTL (Figs. 3a and 5a). Indeed, in the northern section of the N-S transect of BL, the presence of ice sheets and cool oceans causes the July temperatures to deviate strongly from the CTL values (Fig. 3a). In addition, these 'cooling' factors result in lower temperatures in LP compared to CTL. The July profiles derived from the YD experiment form an exception, as the YD July temperatures are substantially lower than in the other simulations, especially along the east-west transect (Fig. 5a). This difference can be attributed to the application of a basic permafrost parameterisation in the YD experiment, which forces the model to maintain a wet and cold subsoil in areas with permafrost (i.e. north of 50°N, Isarin, 1997; Renssen et al., 2000).

Prescribed vegetation changes are expected to have played a minor role. In Renssen and Lautenschlager (2000) the effect of vegetation changes on the model climate was investigated. It was found that especially vegetation-related changes in surface albedo might result in temperature anomalies of several degrees Celsius. However, in the experiments described here, the prescribed surface albedo does not vary much throughout Europe (Renssen & Isarin, 2001). An exception is PB, in which the albedo of a closed forest vegetation was defined in Europe. This 'forest' albedo is lower than that of vegetation with sparse tree cover or without trees described in other experiments. Consequently, a part of the relatively high continental temperatures in PB may be attributed to the effect of vegetation.

Discussion and conclusions

Comparison with reconstructed temperatures

The simulated January profiles of PB, BL and LP are in general agreement with the reconstructed January temperatures depicted in Fig. 2b and 4b. Exceptions are the southern section of the N-S profile (near the Mediterranean Sea), and the western part of the E-W profile (near the Atlantic) where the model produces higher temperatures. In addition, the simulated YD January climate is too warm compared to the reconstructions. This model-data mismatch is noted north of 46°N in the north-south profile (compare Figs. 2a and 2b) and west of 15°E in the east-west profile (Figs. 4a and 4b), and increases towards the Atlantic coast. The proxy data suggest that, during the Younger Dryas, the January temperature profile was similar to that of the Late Pleniglacial. This supports our earlier findings that the winter sea ice margin must have been located at a more southerly position (e.g., 45 to 50°N) than the latitude of 55-60°N prescribed in experiment YD (Renssen & Isarin 1998, Isarin et al., 1998).

The reconstructed July temperatures for the Preboreal and early Bølling suggest that the simulated values for these time-slices may be about 6° C too high over the continental interior (compare Figs. 3a and 5a with Figs. 3a and 5b). In the east-west transect, the reconstructed values are between 14 and 16° C, whereas the simulated July temperatures are 21 to 22° C. It should be noted, however, that these reconstructions are based on climate indicator plant species and that beetle-based estimates are a few degrees higher (Coope et al., 1998). Nevertheless, this model-data mismatch could be related to unrealistic drying of the soil due to relatively high insolation values. The latter would depress evaporation values and make most energy available for heating of the lower atmosphere. Simplification of the soil-hydrology is a known weakness of climate models, including ECHAM, which contains a simple 'bucket' model. This weakness is illustrated by the results that we obtained in the YD-experiment which are in agreement with proxy data. In this simulation, we applied a basic permafrost parameterisation that forces the model to keep a wet and cold soil (see Renssen et al., 2000). In the YD-results the July temperatures are indeed in agreement with the reconstructed values (compare Figs. 3a and 5a with Figs. 3b and 5b). We did not apply this permafrost parameterisation in LP because we expected that, given the prescribed glacial boundary conditions, the model was able to simulate 'permafrost-like' soil conditions without external forcing. The absence of periglacial features dated to BL and PB suggests that permafrost mostly had disappeared from Europe during these phases. Clearly, the model-data comparison suggests that the model could be improved by including a more realistic soil module.

Climate change in The Netherlands compared to surrounding regions

Our results for The Netherlands are summarized in Fig. 6. At 14.7 ky BP both the model (dashed line in Fig. 6) and data reconstructions (full line in Fig. 6) produce comparable temperature increases of 3-6° C in summer and 15 to 17° C in winter. A similar result is obtained for the summer warming at 11.5 ky BP. However, in the two periods the model results show higher temperatures than the reconstructions based on proxy data. Moreover, the model results show a much higher winter temperature during the Younger Dryas than the proxy data. In Renssen and Isarin (1998) it was argued that this disagreement is caused by a winter sea ice margin that was assumed too much to the north in the YD model experiment. It follows that the increase in winter temperature at 11.5 ky was similar in magnitude to the warming at 14.7 ky.

Considering our transects for the cold phases (Younger Dryas and Late Pleniglacial), the January temperature gradients were most pronounced in a north-south direction. Thus, in contrast to the present climate (and Preboreal and Bølling), the winter temperatures in The Netherlands were not very different from temperatures in Eastern Europe. As discussed, this is an effect of the southward expansion of winter sea-ice during cold phases. The simulations suggest that in the warm phases (Preboreal and Bølling) the east-west gradient was a little steeper than today (Fig. 4a), implying that the winters were relatively cooler in Eastern Europe than in The Netherlands.

If we look at the change in temperature through time, the largest changes between different time-slices are due to latitudinal shifts in North Atlantic Ocean conditions (i.e. sea ice margin and associated polar front), implying that regions closest to the North Atlantic Ocean experienced the strongest temperature changes during the 14.7 and 11.5 cal ky BP transitions. Consequently, compared to The Netherlands, regions to the North and to the West (British Isles, Ireland, W. France and S. Scandinavia) experienced stronger warming during the two climatic shifts. In

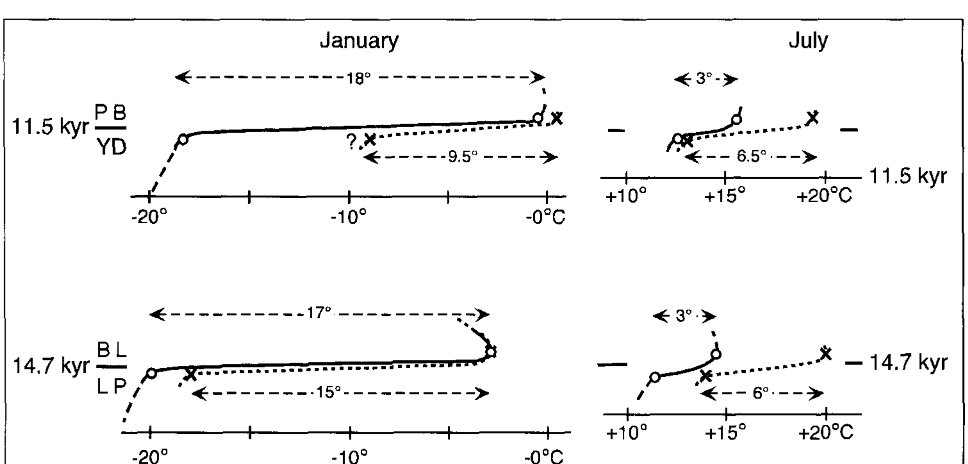

Fig. 6. Mean temperatures of the warmest (July) and coldest months (January) at the climatic transitions from the Late Pleniglacial (LP) to the Bølling period (BL) and from the Younger Dryas (YD) to the Preboreal (PB) in The Netherlands. The dashed line represents model result, whereas the full line gives the reconstruction based on palaeodata.

contrast, during the 14.7 and 11.5 cal ky BP transitions, the changes in Southern, Central and Eastern Europe were smaller than in The Netherlands.

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