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# Simulation of the Younger Dryas climate in Europe using a regional climate model nested in an AGCM: preliminary results

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#### Abstract

The REMO regional climate model was applied for a simulation experiment on the European climate of the Younger Dryas, a distinct cooling event at the end of the last glacial. This regional simulation—with a  $0.5 \times 0.5^{\circ}$  latitude–longitude resolution—was 'nested' in an experiment carried out with the ECHAM4/T42 atmospheric general circulation model. The objective is to evaluate the advantages of a regional climate model (compared to a global model) for palaeoclimate research. Therefore, we compared our regional and global Younger Dryas experiments with climate reconstructions based on palaeodata. The comparison reveals that both models simulate a similar Younger Dryas climate. In some instances, REMO simulates a YD climate that is in better agreement with palaeodata than ECHAM4, most notably for precipitation and winter temperatures. Moreover, the higher spatial resolution of REMO, giving a more realistic presentation of the topography, provides regional climatic information, such as precipitation and temperature gradients, that is valuable for palaeoclimate data studies. Consequently, our results illustrate the perspective of regional climate models for palaeoclimate studies. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: simulation; climate change; high-resolution methods; general circulation models; Europe; Younger Dryas

# 1. Introduction

Since the 1970s, numerical climate models have been used to study past climates. The most frequently applied models are general circulation models (GCMs) that simulate the atmospheric circulation at a global scale. For instance, GCMs have been used to simulate the climates of the last glacial maximum (LGM, ~ 21 kyears BP, i.e. 21,000 years before present; e.g., Gates, 1976; Kutzbach and Guetter, 1986; Lautenschlager and Herterich, 1990), the Younger Dryas event (YD, ~ 12 kyears BP; Rind et al., 1986; Renssen, 1997; Fawcett et al., 1997) and the mid-Holocene (6 kyears BP; e.g. Harrison et al., 1998; Joussaume et al., 1999). To

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analyse model performance, the results of these studies have been compared with climate reconstructions based on palaeodata (e.g. Kutzbach and Wright, 1985; Texier et al., 1997; Renssen and Isarin, 1998; Kohfeld and Harrison, 2000). However, the differences in spatial scale between model results and reconstructions often pose a problem. GCMs cover the entire globe and have coarse resolutions with a typical distance between grid points of 200-500 km. In contrast, palaeoclimate reconstructions are usually created for specific regions and are therefore more detailed (Crowley and North, 1991). Consequently, to make GCM-data comparisons meaningful, large and spatially extensive proxy datasets are required to make reconstructions that cover at least a continent (Isarin and Renssen, 1999). However, such datasets are only available for ideal time-periods. Using downscaling techniques may solve this spatial-scale problem. It should be noted that downscaling does not resolve the differences in temporal scale between climate simulations (mean for  $\sim 500-1000$  years) and proxy data (representing shorter time-periods). This follows from the boundary conditions used to drive palaeoclimate experiments, which often represent average conditions for at least 500 years (for example, ice sheet extent and sea surface temperatures), implying that the simulated climate is to be considered as a 500-year mean.

Downscaling methods may be divided into statistical and dynamical techniques. Statistical techniques are based on relationships between measurements of local modern climate and the climate simulated in larger-scale models. These relationships may be based on regression, circulation patterns or stochastic weather generators. In studies of climate change, typically, GCMs are applied to simulate the globalscale climate following a certain scenario and, subsequently, the statistical relations are used to infer the local climate (Mitchell and Hulme, 1999). In contrast, dynamical techniques make use of physically based climate models with a higher spatial resolution. These models may be GCMs with a grid that is variable, so that the resolution can be optimised for the region of interest (e.g. Deque and Piedelievre, 1995). Alternatively, regional climate models (RCMs) can be 'nested' in a GCM. This procedure involves the definition of a certain regional domain, for which the RCM simulates the climate at a relatively high resolution (i.e. 50–70 km), while the lateral boundary conditions are produced by a GCM (e.g. Giorgi, 1990; Giorgi et al., 1990; Giorgi and Mearns, 1991; Jones et al., 1995). It should be realised that in the latter procedure, potential systematic errors in the GCM are transferred to the RCM. Despite its potential, the 'nested' approach has only been applied in a few palaeoclimate studies. For instance, Hostetler et al. (1994) simulated the LGM climate of the western USA with a nested RCM. However, to our knowledge, no studies using this nested technique have been published for simulations of the palaeoclimate in Europe.

We applied this 'nested' method to perform a simulation of the Younger Dryas (YD, or Greenland Stadial 1; Björck et al., 1998) climate in Europe. YD is a distinct cold period at the end of the last glacial (around 12 kyears BP) that is clearly registered in geological records surrounding the Atlantic Ocean (see, e.g. Lowe et al., 1995; Walker, 1995). In this paper, we present the results of an integration with YD surface boundary conditions that was performed with the REMO-RCM developed at the Max-Planck-Institute for Meteorology (Jacob and Podzun, 1997, 2000). This integration was nested in a YD simulation carried out with the ECHAM4 AGCM (see Renssen et al., 2000). Our aim is to evaluate the advantages of the use of an RCM for palaeoclimate research, by comparing the regional and global simulation results with palaeodata, giving information on the YD climate in Europe (e.g. Isarin, 1997; Renssen and Isarin, 1998; Isarin and Bohncke, 1999). As computing costs for nested experiments are relatively high, we restricted the duration of the nested integration to 3 years. We realise that an experiment with a 3-year duration is too short to make decisive conclusions and, therefore, we consider our results as preliminary.

#### 2. Methods

#### 2.1. AGCM

Global-scale experiments were performed with the ECHAM4 (European Centre HAMburg) AGCM of the Max-Planck-Institute (MPI) for Meteorology, Hamburg. This spectral AGCM, with 19 atmospheric

(a)

layers, is capable of simulating satisfactorily the main features of the modern global circulation (Roeckner et al., 1996). We applied the T42-version, which translates to horizontal resolution of  $\sim 2.8^{\circ}$  latitude–longitude. A detailed description of the ECHAM4 model can be found in Roeckner et al. (1992, 1996) and Deutsches Klimarechenzentrum (1994).

# 2.2. RCM

The regional model used in this study is the REMO (REgional MOdel) RCM that was developed by the MPI for Meteorology, together with Deutsches Klimarechenzentrum (DKRZ). Forschungszentrum Geesthacht (GKSS) and Deutscher Wetterdienst (DWD). REMO is based on the Europa-Model developed at DWD. In addition to the physical parameterisation packages of the Europa-model, the physical parameterisation schemes used in the global climate model ECHAM4 were implemented. We applied the version of REMO with physics equivalent to those in the ECHAM4 model. The spatial resolution of the REMO-version used in this study consists of a surface grid of 0.5° longitude by 0.5° latitude and 20 layers in the vertical direction (Jacob and Podzun, 1997). We used the standard domain for Europe, with  $81 \times 91$  grid points and rotated spherical coordinates with the North Pole at 170°W, 32.5°N (see Fig. 1a). In our experiments, REMO uses 6-hour updates of the following ECHAM time-varying fields as lateral boundary conditions: surface pressure, horizontal velocities, temperature and moisture. The prognostic variables in REMO are relaxed towards these lateral boundary conditions in a zone of eight grid rows towards margins of the domain, following a scheme of Davies (1976). The REMO results near these margins may be unrealistic due to the nesting procedure and are not considered in the analysis.

# 2.3. Experimental design

The results of two ECHAM4-T42 experiments are discussed in this paper (see Table 1). The first experiment (T42-CTL) is a simulation of the modern climate, in which present-day boundary conditions were prescribed. The used sea surface temperatures (SSTs) were based on the 1979–1988 mean (i.e.



REMO

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Fig. 1. Land-ice-sea mask for YD conditions (dark grey = land ice, grey = land, white = sea). (a) REMO model  $(0.5 \times 0.5^{\circ}$  latitude-longitude), shown area is 'nested' domain, (b) ECHAM4-T42 ( $\sim 2.8 \times \sim 2.8^{\circ}$  latitude-longitude).

so-called climatological SSTs) that was compiled from various sources by Reynolds (1988). The duration of T42-CTL was 16 model years, of which the first 2 years are discarded to account for model spin-up.

In the second ECHAM4-T42 experiment (T42-YD, 12-year duration), we prescribed the following boundary conditions according to the YD situation: ocean surface conditions (SSTs and sea ice), ice sheets, land-sea distribution, vegetation parameters, concentration of greenhouse gasses (i.e.  $CO_2$ ,  $CH_4$ ,  $N_2O$ ), insolation and permafrost. The prescribed SSTs were lowered (compared to T42-CTL) in the Atlantic and Pacific Oceans in agreement with ocean model experiments (Schiller et al., 1997) and geolog-

	T42-CTL (14 years)	T42-YD (10 years)	REMO-CTL (10 years)	REMO-YD (3 years)
SSTs + sea ice	0 k	YD in N Atlantic; - 2°C in N Pacific	0 k	YD in N Atlantic
Ice sheets	0 k	12 k	0 k	12 k
Insolation	0 k	12 k	0 k	12 k
$CO_2/CH_4/N_2O$	353/1720/310	246/500/265	353/1720/310	246/500/265
Vegetation parameters	0 k	YD	0 k	YD

Table 1 Design of the experiments, results of which are shown in this paper ('k' denotes kyears BP)

The atmospheric concentration of  $CO_2$  (ppm),  $CH_4$  (ppb) and  $N_2O$  (ppb) is based on Antarctic ice core analyses by Raynaud et al. (1993). Experiment REMO-CTL was nested in T42-CTL and REMO-YD was nested in T42-YD.

ical data (Sarnthein et al., 1995). A cooling of up to 10°C was prescribed in the Atlantic Ocean north of 30°N, resulting in a southward expansion of sea ice (Sarnthein et al., 1995). The sea ice margin was situated at 70°N in summer and at 55°N in winter (see Renssen, 1997 for details). In the N Pacific, a cooling of 2°C was defined north of 40°N. in accordance with ocean core analysis (e.g. Kallel et al., 1988) and coupled atmosphere-ocean model experiments (Mikolajewicz et al., 1997). As suggested by marine data (Schulz, 1995; Thunell and Miao, 1996), we assumed that no ocean cooling occurred in the tropics during the YD. Ice sheet topography was defined according to Peltier (1994), and insolation was prescribed following Berger (1978). The following parameters were changed to give a representation of the YD vegetation reconstruction of Adams (1997): surface background albedo, leaf area index, vegetation ratio, forest ration and roughness length (see Renssen and Lautenschlager, 2000). A simple permafrost parameterisation was applied by taking the following two measures for grid cells where permafrost was present during YD: (1) fixed sub-zero temperatures in the lowest two soil layers, (2) soil humidity fixed at field capacity (see Renssen et al., 2000). Note that experiment T42-YD is discussed in detail elsewhere (Renssen et al., 2000; Renssen and Isarin, 2001).

Analogous to the ECHAM4 simulations, we carried out two experiments with REMO to simulate the modern and YD climates (viz. REMO-CTL and REMO-YD, see Table 1). These REMO experiments were nested in the ECHAM4 experiments described above, i.e. REMO-CTL in T42-CTL and REMO-YD in T42-YD. In the domain shown in Fig. 1a, we prescribed YD surface parameters that were based on

the same sources as in the ECHAM4 simulation. Maps of these boundary conditions (i.e. vegetation parameters and ice sheet orography) were digitised onto the 0.5° grid to obtain input files for REMO. In addition, we altered the land-sea mask to take the  $\sim 60$  m lower sea level into account (Fairbanks. 1989). It should be noted that no additional details have been added to the fields of vegetation parameters (e.g. due to regional vegetation differences), so that the spatial resolution of these parameters is comparable in REMO-YD and T42-YD. Fig. 1a.b shows the land-ice-sea masks for the YD experiments, for both ECHAM and REMO, for a direct comparison. Obviously, the land-ice-sea mask used in REMO provides much more detail than that of ECHAM. This is also true for the surface elevation prescribed in both models. It is expected that these differences will produce corresponding spatial details in the simulation results, most notably in surface temperature and precipitation.

# 3. Results

#### 3.1. Introduction to the results presented

We focus our analysis on surface variables, as reconstructions based on palaeodata are available for the surface climate. Recently, reconstructions of the YD surface temperatures in Europe—based on palaeobotanical and periglacial data—became available (Isarin, 1997; Isarin and Bohncke, 1999). Moreover, fossil aeolian features provide information on the high-intensity winds and on the atmospheric circulation during YD time (Isarin et al., 1997). Furthermore, studies on former lake levels and river regimes give qualitative information on past variations in precipitation (Bohncke et al., 1988; Bohncke, 1993; Magny and Ruffaldi, 1995; Huisink, 1997). Considering these palaeodata, we present in the following section the simulated results of the mean sea level pressure (MSLP), the surface (2 m) temperature and the total precipitation.

# 3.2. MSLP

The simulated MSLP fields of REMO-CTL and REMO-YD look alike (see Fig. 2a–d), although marked differences are also present. During DJF (December–January–February), similar pressure gradients are present, showing evidence for a strong zonal flow. However, in Fig. 2c (REMO-YD), the

flow appears to be slightly more southwesterly than in Fig. 2a (REMO-CTL), and the absolute MSLP values are about 10 hPa higher over W Europe. A comparison of the JJA (June–July–August) results of REMO-CTL and REMO-YD reveals higher MSLP values in the latter experiment over Scandinavia and the Nordic seas, presumably due to the surface cooling over the Scandinavian ice sheet and the cold ocean surface (Fig. 2b,d).

A comparison of the ECHAM4 MSLP results for T42-CTL and T42-YD (Fig. 3a–d) also reveals some marked deviations. In the DJF plot for T42-YD (Fig. 3c), a steeper pressure gradient is visible over NW Europe compared to the result for T42-CTL (Fig. 3a). This is caused by a more eastward position of



Fig. 2. Simulated mean sea level pressures (in hPa). (a) DJF mean experiment REMO-CTL, (b) JJA mean experiment REMO-CTL, (c) DJF mean experiment REMO-YD, (d) JJA mean experiment REMO-YD. Contour interval: 2 hPa.



Fig. 3. Simulated mean sea level pressures (in hPa). (a) DJF mean experiment T42-CTL, (b) JJA mean experiment T42-CTL, (c) DJF mean experiment T42-YD, (d) JJA mean experiment T42-YD. Contour interval: 2 hPa.

the Icelandic Low in Fig. 3c. A comparison of Fig. 3a,c also shows that the absolute MSLP values are higher in T42-YD, although this anomaly is smaller than noted for the REMO results. The JJA-plots for T42-YD and T42-CTL are again similar (Fig. 3b,d), although the MSLP values are a few hPa higher in Fig. 3d (T42-CTL), especially near the Atlantic Ocean.

#### 3.3. Surface temperature

The REMO-plots for the surface temperature show clearly the impact of the YD boundary conditions (see Fig. 4a–f). In the DJF result for REMO-CTL (Fig. 4a), temperatures increase in an E–W direction towards the Atlantic Ocean from  $-20^{\circ}$ C in N Russia to 10°C near the coast. In contrast, in Fig. 4c (REMO-YD DJF result), a N–S gradient is present, with values of  $-35^{\circ}$ C in northern Scandinavia to  $-10^{\circ}$ C at 50°N, and 5°C at the Mediterranean coast. In the REMO-YD minus REMO-CTL anomaly plot for DJF, the cooling is largest in N Europe, reaching 30°C along the Scandinavian coast. In NW Europe, the anomaly lies between 20°C and 10°C, while in S Europe, it is about 5°C. The simulated JJA temperatures for REMO-CTL (Fig. 4b) vary between 10°C in N Europe to over 25°C in the south of the domain, whereas for REMO-YD (Fig. 4d), they range from 0°C over Scandinavia to 25°C in S Europe. The JJA anomaly plot (Fig. 4f) shows that a cooling is simu-



Fig. 4. Simulated mean surface (2 m) temperatures (in °C). (a) DJF mean experiment REMO-CTL, (b) JJA mean experiment REMO-CTL, (c) DJF mean experiment REMO-YD, (d) JJA mean experiment REMO-YD, (e) DJF REMO-YD minus REMO-CTL difference, (f) JJA REMO-YD minus REMO-CTL difference. Contour interval: 5°C (except for panel f of this figure; contours at  $-20^{\circ}$ C,  $-15^{\circ}$ C,  $-10^{\circ}$ C,  $-5^{\circ}$ C,  $-2^{\circ}$ C,  $-1^{\circ}$ C,  $0^{\circ}$ C,  $1^{\circ}$ C and  $2^{\circ}$ C).



Fig. 5. Simulated mean surface (2 m) temperatures (in °C). (a) DJF mean experiment T42-CTL, (b) JJA mean experiment T42-CTL, (c) DJF mean experiment T42-YD, (d) JJA mean experiment T42-YD, (e) DJF T42-YD minus T42-CTL difference, (f) JJA T42-YD minus T42-CTL difference. Contour interval: 5°C (except for panel f of this figure; contours at  $-15^{\circ}$ C,  $-10^{\circ}$ C,  $-5^{\circ}$ C,  $-2^{\circ}$ C,  $-1^{\circ}$ C,  $0^{\circ}$ C,  $1^{\circ}$ C and  $2^{\circ}$ C).

lated in N–NE Europe (more than 10°C) and along the coast (few degrees), whereas over most of the interior of the continent, the values are similar in REMO-CTL and REMO-YD. An exception to this pattern is visible over the S North Sea region, where a positive JJA temperature anomaly of 2°C is apparent in Fig. 4f. The latter can be supposedly explained as an effect of the different land–sea masks used in both experiments, causing the S North Sea region to be defined as land in REMO-YD and as sea in REMO-CTL. Consequently, in REMO-YD, the region is heated in summer more easily than in REMO-CTL, in which the temperature is determined by the prescribed SSTs.

As expected, the REMO temperature results are consistent with the ECHAM4 results (Fig. 5a-f). The T42-CTL plots (Fig. 5a,b) are very similar to their REMO counterparts (Fig. 4a.b), although less details are present. Also, in Fig. 5b (JJA T42-CTL), the temperatures are somewhat lower than in Fig. 4b (JJA REMO-CTL), in SE Europe and in SW France. Compared to the REMO results, the YD results produced by ECHAM4 (Fig. 5c-d) give slightly higher temperatures for DJF and generally lower values for JJA. The most striking difference between the DJF anomaly plot (Fig. 5e, T42-YD minus T42-CTL) and its REMO counterpart (Fig. 4e) is the less intense cooling between 50°N and 60°N in the ECHAM result. In general, the simulated JJA anomalies of ECHAM4-T42 (Fig. 5f) and REMO (Fig. 4f) are comparable. An exception forms NW Europe, where ECHAM4 produced a cooling of around 5-10°C, whereas in the REMO-result, the JJA-anomalies are slightly negative  $(-1^{\circ}C \text{ to } -5^{\circ}C)$ along the coastal region and slightly positive  $(0-1^{\circ}C)$ in the interior of France and the Low Countries. The JJA temperatures in the S North Sea region are relatively high, as can be seen by northward excursions of the  $10^{\circ}$ C and  $-5^{\circ}$ C isotherms in the T42-YD and YD-CTL anomaly plots, respectively (Fig. 5d,f). A similar effect was seen in the REMO results, and was explained by the differences in land-sea masks. However, the T42-YD temperatures do not exceed the T42-CTL values, as is the case with REMO.

To further investigate the differences in temperature between REMO-YD and T42-YD, we looked at the interannual variation in both experiments. The performance of statistical tests was not feasible due

to the limited duration of REMO-YD (i.e. 3 years). Instead, we plotted the seasonal means for the area where the largest differences were noted: between  $50^{\circ}N-60^{\circ}N$  and  $10^{\circ}W-30^{\circ}E$  (see Fig. 6a.b). For REMO-YD, the means are an approximation for this area, as REMO uses a rotated grid instead of a rectangular latitude-longitude grid. As seen in Fig. 6a, the interannual range of T42-YD for DJF has lower and upper limits of  $-18^{\circ}$ C and  $-9^{\circ}$ C, respectively. The mean DJF temperature of the first year in REMO-YD (i.e.  $-16.5^{\circ}$ C) falls in this interannual range of T42-YD, whereas the other two REMO-YD values are lower. The 3-year mean of REMO-YD is clearly outside this range, with a value of  $-19.6^{\circ}$ C. For JJA, the picture is unambiguous, as all three seasonal means of REMO-YD have higher values than the upper limit of the interannual range (Fig. 6b). The noted positive difference in JJA temperature between REMO-YD and T42-YD is probably due to the permafrost parameterisation, which was applied in T42-CTL but not in REMO-YD. As discussed in Renssen et al. (2000), this permafrost parameterisation depressed summer temperatures by up to 5°C in T42-YD compared to T42-CTL. We performed a similar exercise as plotted in Fig. 6a,b for REMO-



Fig. 6. Seasonal mean temperatures for individual years averaged over an area in the centre of the domain (limits:  $50^{\circ}N-60^{\circ}N$  and  $10^{\circ}W-30^{\circ}E$ ), as simulated in T42-YD (closed boxes) and REMO-YD (closed triangles). (a) DJF, (b) JJA. The open figures are the multi-year means, with the interannual range shown for the T42-YD mean by  $\pm 2$  standard deviations.



Fig. 7. Simulated mean total precipitation (in mm/day). (a) DJF mean experiment REMO-CTL, (b) JJA mean experiment REMO-CTL, (c) DJF mean experiment REMO-YD, (d) JJA mean experiment REMO-YD, (e) DJF REMO-YD minus REMO-CTL difference, (f) JJA REMO-YD minus REMO-CTL difference. Contour interval: 1 mm/day.



Fig. 8. Simulated mean total precipitation (in mm/day). (a) DJF mean experiment T42-CTL, (b) JJA mean experiment T42-CTL, (c) DJF mean experiment T42-YD, (d) JJA mean experiment T42-YD, (e) DJF T42-YD minus T42-CTL difference, (f) JJA T42-YD minus T42-CTL difference. Contour interval: 1 mm/day.

CTL and T42-CTL. This indicated that the interannual ranges of the two experiments overlap to a large degree (not shown). To conclude, the differences between REMO-YD and T42-YD appear to be meaningful, but the limited duration of REMO-YD makes it impossible to reach a decisive conclusion on this matter.

# 3.4. Total precipitation

The precipitation values simulated by REMO (Fig. 7a-f) clearly show the influence of topography, since the highest values (up to 6-7 mm/dav) are produced in mountainous regions such as Scandinavia, Scotland and the Alps. In the DJF-season, there is more precipitation than in summer. In the DJF result for REMO-YD (Fig. 7c), the zone with precipitation is more latitudinally restricted, as opposed to the result of REMO-CTL (Fig. 7a)-the values are very low (less than 1 mm/day) in the N Scandinavia and over the Mediterranean. However, the core of the DJF storm track is more intensive in REMO-YD than in REMO-CTL, as is seen by the positive anomaly over W Europe (see Fig. 7e; > 1 mm/day over the Irish Sea). In the JJA season, the REMO-YD minus REMO-CTL anomaly is negative over the entire continent. The magnitude of this negative anomaly increases from west to east (i.e. going inland, see Fig. 7f).

Again, the REMO results are consistent with the ECHAM4 results, although the topographic effect is barely present (Fig. 8a–f). The DJF storm track is also narrower in the YD-result (Fig. 8c) compared to the control experiment (Fig. 8a). Moreover, the core of the main precipitation belt has shifted southward from 60°N (Fig. 8a) to about 52°N (Fig. 8c). As a result, a small positive anomaly is visible over Britain in Fig. 8e (compare with REMO result in Fig. 7e). In the JJA anomaly plot, the deviation is generally negative over the continent (see Fig. 8f).

#### 4. Discussion

# 4.1. What was the YD climate in Europe like according to palaeodata?

A compilation of aeolian data from NW Europe revealed that prevalent dune-forming winds during

the YD were all westerly (Isarin et al., 1997). Presumably, these winds represent the average winter circulation regime. Moreover, temperature reconstructions for the European YD climate suggest a N-S thermal gradient and very low winter temperatures, ranging from  $-25^{\circ}$ C at 55°N to  $-15^{\circ}$ C at 50°N (see Fig. 9a: Isarin et al., 1998). These values translate to a cooling, compared to today, ranging from 30°C in Ireland and Britain to 15°C in Russia. The summer conditions were less dramatic, with temperatures varying from 10°C in Scotland and S Sweden, to 15°C in central France (Fig. 9b: Isarin et al., 1998). These temperatures imply a cooling of  $3-6^{\circ}C$  compared to today. It should be realised that the uncertainty of these reconstructions is estimated at  $\pm 2^{\circ}$ C (Isarin and Bohncke, 1999). Furthermore, several studies suggest that the early part of the YD was a relatively wet phase in W Europe, as indicated by high lake levels and by increased river activity (e.g. Vandenberghe and Bohncke, 1985; Bohncke, 1993; Magny and Ruffaldi, 1995; Huisink, 1997). According to these same studies, the later part of YD seems to have been drier. It should be noted that this view is not coherent throughout Europe, as in N Norway and in Poland, the early YD was drier than the later part (e.g. Goslar et al., 1993; Birks et al., 1994; Walker, 1995). Assuming that these discussed palaeodata are reliable, we can evaluate our YD simulations by comparing the results with these data.

# 4.2. Is REMO producing a more realistic YD climate than ECHAM4?

The MSLP plots for REMO and ECHAM both show a strong westerly flow over W Europe (see Figs. 2c and 3c) during winter. This is in agreement with westerly dune-forming winds as reconstructed with the aid of aeolian features (Isarin et al., 1997). We see no evidence for a glacial anticyclone over the Scandinavian ice sheet (Figs. 2c–d and 3c–d), as was simulated in several GCM simulation studies on the LGM climate (e.g. Kutzbach and Wright, 1985; Rind, 1987). Consequently, the REMO results confirm our conclusions from earlier studies that westerly flow was dominant in Europe during the YD (Renssen et al., 1996; Isarin et al., 1997, 1998). This westerly flow transported cold air (cooled over the extended N Atlantic sea ice) to NW Europe.



Fig. 9. Reconstructed temperatures at sea level in NW Europe for the Younger Dryas. (a) Winter (maximum mean coldest month) isotherms (°C, bold), and differences from the present (°C, italic). (b) Summer (minimum mean warmest month) isotherms (°C, bold) and differences from the present (°C, italic). From Isarin et al. (1998). Reproduced with kind permission of John Wiley&Sons.

REMO produced winter (DJF) temperatures that are in better agreement with the reconstructions than the result of ECHAM4. It should be realised that the difference between REMO-YD and T42-YD should be treated with caution (see discussion of Fig. 6a). The better agreement is seen in northern Europe (north of 50°N), where REMO-YD simulates lower temperatures than T42-YD. For instance, in both the reconstruction and the REMO-YD result, the  $-25^{\circ}$ C isotherm is situated over S Scandinavia, whereas in Fig. 5c, the temperature in this region is from  $-15^{\circ}$ C to  $-20^{\circ}$ C. This is also visible in the YD-CTL anomaly plots, where REMO produces a cooling of more than 20°C in Scandinavia, in agreement with the reconstruction (compare Figs. 4e and 9a), whereas the ECHAM-result suggests a cooling between 15°C and 20°C in this area. However, near the Atlantic coast, both experiments suggest generally a warmer

winter climate in Europe than the reconstructions. For example, in Ireland, a winter temperature of  $-20^{\circ}$ C to  $-25^{\circ}$ C is reconstructed using geological data (Fig. 9a), while a value from 0°C to  $-15^{\circ}$ C is simulated (Figs. 4c and 5c). The latter model-data mismatch is probably caused by the prescribed winter sea ice margin, which is located at 60°N near the W European coast in REMO-YD and T42-YD. Renssen and Isarin (1998) argued that during YD, this sea ice margin was probably situated at 52°N, thus explaining the reconstructed temperature of  $-25^{\circ}$ C in Ireland. Hence, the extended N Atlantic sea ice cover played a key role in forcing the YD winter temperatures in Europe (Isarin et al., 1998; Renssen and Isarin, 1998).

The model-data comparison for the summer (JJA) temperatures gives an ambiguous picture. In NW Europe, the summer temperatures in the REMO-YD result are higher than those generated by T42-YD. For instance, the temperature between 50°N and 55°N is over 15°C in the REMO-YD result (Fig. 4d), whereas this value in T42-YD ranges from 10°C to 15°C (Fig. 5d). The latter model result corresponds better with the reconstruction (Fig. 9b). As noted before, the difference in JJA temperatures between REMO-YD and T42-YD can be attributed to the use of a permafrost parameterisation in T42-YD, which produces an additional depression of the surface temperatures (Renssen et al., 2000). In addition, it is noted that the reconstructed temperatures are minimum values, meaning that they could have been higher in reality (see Isarin and Bohncke, 1999).

The precipitation fields simulated by REMO are in general agreement with the discussed palaeodata. For winter, there is a tendency of precipitation increase in W Europe (see Fig. 7e; YD-CTL anomaly), whereas there is a negative anomaly visible over the rest of Europe. In summer, the YD-CTL anomaly is negative everywhere on the continent (Fig. 7f). In the T42-YD result, the same trend is visible, with a slight precipitation increase near the Atlantic coast compared to T42-CTL. It should be realised, however, that ECHAM4 has a highly smoothed topography, making the simulation of orography-induced precipitation a weak point in this model. In earlier studies, we explained the relatively high precipitation values during the YD by a positioning of the main storm track over NW Europe (Renssen et al., 1996; Isarin et al., 1998). Today, this main storm track is located more to the North (i.e. between Scotland and Iceland). Thus, whereas in most places, precipitation was reduced during the YD (due to the lower water content of cold air; c.f. Rind, 1987), precipitation increased over NW Europe as a result of the position of the main storm track. During winter, this position of the storm track was directly related to the location of the Atlantic sea ice margin (see Renssen et al., 1996).

In summary, the YD climates simulated by REMO and ECHAM4 are very similar on a continental scale, although some differences are noted. The model-data comparison shows that REMO generates winter temperatures that are in better agreement with proxy data. The opposite is true for JJA temperatures, which are better reproduced by ECHAM4 due to the application of a permafrost parameterisation. We may conclude that, considering palaeoclimate research, the biggest advantage of the use of an RCM instead of an AGCM, lies in the more detailed information that is provided. For instance, someone studying palaeoclimate records, obtained from the coastal region of Scandinavia, would be very interested to receive information on the gradients in temperature and precipitation provided by the RCM. It is very likely that these regional records have been influenced by these gradients, so that the spatial scale of the RCM is here in better agreement with the data than an AGCM would be. Once again, it should be noted that our REMO-YD experiment has a duration of only 3 years, which is generally considered too short for climate studies. Therefore, our results should be regarded as preliminary. We think, however, that our results provide a good starting point for future palaeoclimate studies using nested RCMs.

# 5. Conclusions

We simulated the Younger Dryas climate in Europe with the REMO regional climate model nested in an AGCM simulation, performed with the EC-HAM-T42 model. Such a regional simulation of a palaeoclimate in Europe has not been performed before. Note that our REMO simulation on the Younger Dryas has a duration of only 3 years, and

that we consider our conclusions as preliminary. A comparison of these REMO and ECHAM4 simulation results on the one hand, with climate reconstructions based on palaeodata on the other hand, suggests the following:

(1) The Younger Dryas climates produced by the REMO and ECHAM4 models are similar on a continental scale. Both REMO and ECHAM4 produced higher winter temperatures  $(0-10^{\circ}C)$  in W Europe than indicated by palaeodata (from  $-15^{\circ}$ C to  $-25^{\circ}$ C). We suggest that this model-data mismatch is caused by the winter sea ice margin, which probablv was located further south (at 52°N) during the Younger Drvas, than prescribed in the simulation experiments. Some differences between the two models have also been found. REMO simulated YD winter temperatures (from  $-20^{\circ}$ C to  $-35^{\circ}$ C) in Scandinavia that correspond well with reconstructions. ECHAM4 gives a too warm climate for this area. On the other hand, compared to the ECHAM4result, REMO generated higher YD summer temperatures in continental Europe. It appears that the ECHAM4-result is in better agreement with reconstructed summer temperatures, although it must be realised that the latter estimates are minimal values. The difference in summer temperatures is attributed to a permafrost parameterisation that is applied in ECHAM4, but not in REMO. Compared to a modern climate experiment, REMO simulated a precipitation increase over W Europe during winter, whereas a negative anomaly was calculated in the rest of Europe.

(2) In palaeoclimate research, the application of a regional climate model has advantages over the use of a global model, since the higher resolution provides a spatial scale that corresponds to palaeoclimate reconstructions. The detailed precipitation distribution and temperature gradients produced by REMO for the Younger Dryas are more suitable for comparison with regional palaeoclimate studies than the results generated by ECHAM4, in which the topography is highly smoothed.

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