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The climate in The Netherlands during the Younger Dryas and Preboreal: means and extremes obtained with an atmospheric general circulation model

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Abstract

The shift from the cold Younger Dryas phase to the relatively warm Pre-boreal at ~11.5 thousand years BP occurred within 50 calendar years and represents a clear example of rapid climate warming. Geologists and palaeo-ecologists have extensively studied the impact of this shift on the environment in The Netherlands. The global atmospheric general circulation model of the Max-Planck-Institute for Meteorology is applied to perform simulations of the Younger Dryas and Pre-boreal climates. Here detailed results are presented for the grid-cell representing The Netherlands, providing quantified estimates of climatic means and extremes for both periods. The results suggest that the Younger Dryas climate was characterised by cold winters (temperatures regularly below –20 °C) and cool summers (13-14 °C), with a high inter-annual variability, strong fluctuations in temperature, frequent storms and snowfall from September to May. The Pre-boreal climate was a 'continental' version of present-day climate, with cooler winters, warmer summers (~2 °C difference) and more snowfall, but lower wind speeds. Also, the Pre-boreal climate was wetter than the present and Younger Dryas climates. The main driving factors were the low temperatures of the partly sea-ice covered N Atlantic Ocean and the insolation that was very different from today, with more incoming solar radiation during summer (+30 W/m^2) and less during winter (–10 W/m^2). The presented detailed results could be valuable for interpreting palaeo-environmental records and for modelling studies on sedimentological processes during the Late Quaternary.

Keywords: climate change, GCM, Pre-boreal, The Netherlands, simulation, Younger Dryas

Introduction

The last glacial-interglacial transition at ~11.5 cal ky BP (thousand calendar years before present) marks one of the most drastic phases of climate change in Europe during the Quaternary (e.g., Taylor et al., 1993). During this shift from the Younger Dryas (YD, ~12.7-11.5 cal ky BP) phase to the Pre-boreal (PB, ~11.5-8.5 cal ky BP) average annual temperatures in NW Europe increased by at least 10°C within a few decades (e.g., Brauer et al., 1999; Renssen & Isarin, 2001). This transition has been extensively studied, as it represents a clear example of rapid climate warming, thus providing important information on the behaviour of the geo-system during times of climate change.

Certainly, the environment of The Netherlands during the YD and PB is the subject of numerous papers. The vegetation development has been recorded in more than 250 pollen diagrams since the 1950's (e.g., van der Hammen, 1952; Wijmstra & de Vin, 1971; Cleveringa et al., 1977; van Geel et al., 1980/81; Bohncke et al., 1987; Hoek 1997a; see Hoek 1997b for complete reference list). As reviewed by Bohncke (1993) and Hoek (1997b), in The Netherlands the park-like YD vegetation with heath and scattered birch, pine and juniper trees was replaced in the PB by birch forest and later pine forest. Moreover, many papers are published that deal with the geomorphology and sedimentology in The Netherlands during the YD and PB. These studies may be subdivided into studies on fluvial sediments (e.g., Vandenberghe et al., 1987; Weerts & Berendsen, 1995; Kasse, 1995a; Huisink, 1997), aeolian deposits (e.g., Maarleveld, 1961; Vandenberghe, 1991; Kasse, 1995b) and periglacial phenomena (e.g., Maarleveld, 1976; De Groot et al., 1987; Bohncke et al., 1993; Isarin, 1997). The reconstructed changes may be summarised as follows: in The Netherlands rivers changed from high-energetic braided (YD) to low-energetic meandering (PB), high aeolian activity as recorded during the YD diminished in the PB, and discontinuous permafrost present in the YD disappeared in the PB.

Palaeo-environmental data are also used to reconstruct the special climate conditions themselves, which are the main cause of the environmental changes at the YD-PB transition (Bohncke, 1993; Vandenberghe, 1995; Isarin, 1997; Isarin et al., 1997; Isarin & Bohncke, 1999). Reconstructions for the YD-PB transition indicate a ~3°C increase in summer temperatures (from 12°C to 15°C) and a much stronger ~18°C increase in winter temperatures (from −18°C to about 0°C) (Renssen and Isarin, 2001). Likewise, effective precipitation (i.e. P-E) values in The Netherlands appear to have increased in the YD-to-PB transitional period (Bohncke, 1993). Surprisingly however, the wind direction appears to have been south-westerly throughout the period of interest and not easterly as might be expected from an analogy with present-day cold winter conditions (Isarin et al., 1997). These reconstructed climatic conditions have been found to be consistent with experiments performed with atmospheric general circulation models (Renssen & Isarin 1998; 2001). So far, emphasis has been on the mean climate (average yearly, summer and winter temperatures, mean wind direction), as this state is believed to have been best registered in the proxy data. However, in addition to this mean climate state, the extremes of climate are also of interest, as they are likely to have had an important influence on the environment. For instance, extreme storm events probably had a strong effect on aeolian sedimentation and fluvial activity. It is, however, difficult to make estimates of these extreme states from the geological archive. Climate models could be helpful, as they simulate effectively atmospheric variability on a wide range of temporal scales (i.e. days to years), thus providing information on the frequency and occurrence of certain events and the year-to-year variability. It should be realized that extreme events simulated by climate models may only be of an indicative nature, since the simulated period of years is usually too short to obtain reliable estimates. For a thorough review of the use of climate models in palaeo-climatology, including model-data comparisons, the reader is referred to Isarin and Renssen (1999).

In this paper additional detailed climate model results on the YD and PB climates in The Netherlands are presented. These results are obtained with the ECHAM4-T42 atmospheric general circulation model (AGCM) of the Max-Planck-Institute for Meteorology. The objective is to give a more complete overview of the changing climate during the YD-PB transition in The Netherlands by providing quantified estimates of important climate parameters, such as minimum and maximum temperatures and the frequency of snowfall and storms. These detailed results could be valuable for interpreting palaeo-environmental records (e.g., Hoek 1997a, b) and for modelling studies on sedimentological processes during the Late Quaternary (e.g., Leeder et al., 1998; Bogaart & van Balen, 2000).

Methods

The Model

The ECHAM4 (European Centre-HAMburg) AGCM with T42 resolution (~2.8 degrees latitude-longitude or ~260 km) is applied to carry out experiments. This three-dimensional model (19 vertical levels) simulates the global atmospheric circulation, including directly related climatic variables as temperature, wind strength and direction, precipitation and evaporation. ECHAM4 includes both an annual and a diurnal cycle (see DKRZ, 1994 for details). The model is capable of simulating a modern climate that corresponds with observations in most cases (Roeckner et al., 1996). Nevertheless, several errors have been recognised. A known model bias for W Europe includes the tendency to simulate anomalously high summer temperatures (+1°C difference with observations) and to underestimate summer precipitation (see Roeckner et al., 1996). It should be realised that the ECHAM4-T42 model is designed to simulate climate at a sub-continental-to-global scale (> 1000 km), making it less suitable for regional-to-local climate studies (< 500 km). However, the AGCM results presented in this study are, so far, the only source of quantitative detailed estimates available for the YD and PB climates. Moreover, as shown in the results section, the model performs surprisingly well when the grid-scale (i.e., ~250 by 250 km) results are compared with modern observations.

Experimental design

In this paper simulations of the PB and YD climates (called PBexp and YDexp) are presented together with a control experiment of present climate (CTRL) for comparison. The duration of the experiments was 16 (CTRL) and 12 (PBexp and YDexp) years. All model results shown are based on results from the last 10 simulated annual cycles of 360 days each with an output interval of 12 hours. In CTRL present-day boundary conditions are prescribed, including insolation, concentration of greenhouse gases, annual cycle of sea surface temperatures (SSTs), surface elevations, land-sea-ice distribution and land surface characteristics such as albedo and vegetation cover. These boundary conditions are altered in PBexp and YDexp to simulate the conditions of the corresponding periods (see Table 1). YDexp should be considered as a representation of the entire YD, as the time-control of the boundary conditions is insufficient to allow for a distinction between different phases within the YD (cf. Bohncke, 1993).

Sea surface conditions

Most of the sea surface conditions prescribed in the PB and YD experiments are based on palaeo-oceanographic evidence, such as SST and sea-ice reconstructions derived from planktonic foraminifera and diatoms. In PBexp modern ocean conditions were defined, i.e. identical to those used in CTRL. This is in agreement with the reconstructions of Schulz (1995). In YDexp, a cooled N Atlantic ocean was prescribed based on SST reconstructions of Sarnthein et al. (1995) and model results (Schiller et al., 1996). The reader is referred to Renssen (1997) for a full description of the used YD SSTs. Compared to CTRL, SSTs were lowered by 8°C in the N Atlantic at 50°N. As a result of this cooling, the sea-ice margin was positioned further south (~55-60°N in winter, ~70°N in summer) than in the control experiment (~80°N in winter, ~75°N in summer), which is in agreement with the reconstructions of Koç et al. (1993). In the Atlantic south of 30°N present-day SSTs were defined, thus assuming that no ocean cooling took place during the YD in the tropics (cf. Schulz, 1995; Thunell & Miao 1996). In the N Pacific a cooling of 2°C was prescribed north of 40°N (cf. Kallel et al., 1988; Mikolajewicz et al., 1997). It should be noted that the results of AGCM climate simulations are quite sensitive to prescribed SSTs and sea-ice cover. To validate our model results, we compared simulated air temperatures for YDexp and PBexp with reconstructed values for Europe. In both cases, this comparison produced a mismatch for coastal regions of Europe, suggesting that the Atlantic Ocean was cooler during the PB and YD than prescribed in the two experiments (Renssen & Isarin, 1998; 2001). The PB SSTs were probably 1-2°C lower than prescribed, whereas the YD winter sea margin was probably positioned at 50-52°N instead of 55-60°N as in YDexp.

Table 1. Summary of experimental design with the most important boundary conditions mentioned ('k' denotes thousand cal years BP). The atmospheric concentrations of CO_2 (ppm), CH_4 (ppb) and N_2O (ppb) are based on Antarctic ice core analyses (e.g., Raynaud et al., 1993).

Boundary conditions	Experiments		
	CTRL Modern	**PBexp** 'Preboreal'	**YDexp** 'Younger Dryas'
SSTs + sea ice	0 k	0 k	YD in N Atl. –2°C in N Pacific
Ice sheets	0 k	11 k	12 k
Insolation	0 k	11 k	12 k
$CO_2/CH_4/N_2O$	353/1720/310	260/720/270	246/500/265
Vegetation Parameters	0 k	PB	YD

Insolation and greenhouse gases

The insolation was altered according to Berger (1978), resulting in – compared to present – more incoming solar radiation during summer and less during winter. At 50°N, the anomalies compared to CTRL are +34 W/m^2 (PB) and +32 W/m^2 (YD) for July and −11 W/m^2 (PB) and −10 W/m^2 (YD) for January. Furthermore, the atmospheric concentrations of three greenhouse gases were lowered compared to their modern values in CTRL: CO_2, CH_4 and N_2O (see Table 1). The values are based on analyses of air trapped in Antarctic Ice cores (Raynaud et al., 1993; Barnola et al., 1994; Blunier et al., 1995; Flückiger et al. 1999). It should be noted that the dominant part of the greenhouse gas forcing is already incorporated in the prescribed SSTs and sea-ice (cf. Renssen, 1997). Therefore, the expected effect of the changes in greenhouse gas concentration is small compared to that of a cooled ocean surface and insolation.

Topography and land-surface characteristics

In PBexp and YDexp the topography was changed following Peltier (1994) to account for the presence of the Scandinavian and Laurentide ice sheets (see Renssen and Isarin, 2001). The ice-sheet extension is similar in both experiments, whereas the elevation is lowered by a few hundred meters in PBexp compared to YDexp. In addition, sea-cells in the North Sea and Bering Strait regions were converted to land-cells in agreement with sea level reconstructions (e.g., Fairbanks, 1989). Consequently, in both palaeo-experiments the location of The Netherlands was more 'continental' than in the control simulation. Moreover, the characteristics of the land-surface were altered to account for the differences in vegetation. In ECHAM4 vegetation is not dynamically included, but described through a few parameters that are kept constant during a simulation. These parameters are the leaf area index, surface albedo, roughness length, vegetation cover and forest cover (Claussen et al., 1994). The parameters for PBexp and YDexp were altered based on vegetation reconstructions of Adams (1997). The reader is referred to Renssen & Lautenschlager (2000) for a detailed description of the followed procedure. Furthermore, in YDexp a simple parameterisation of permafrost was added, implying frozen subsoil and a permanent high water table in regions where permafrost existed during YD (Renssen et al., 2000a).

Results

Introduction to results presented

In this section model results for the grid cell representing The Netherlands (borders at 50.2 and 53.0°N, 4.2 and 7.0°E, see DKRZ, 1994) are shown in two different ways. First, simulated results of CTRL are compared with modern observations to evaluate the model performance. Second, the results for PBexp and YDexp are presented, which in a later stage are compared with climate reconstructions based on proxy data. The modern measurements are for the reference period 1961-1990 and are derived from five meteorological stations in The Netherlands, i.e. De Bilt, Vlissingen, Eelde, De Kooy and Beek (Krijnen & Nellestijn, 1992). These stations give a good representation of the various conditions within The Netherlands, varying from coastal (Vlissingen and De Kooy) to relatively inland locations (Eelde, Beek and De Bilt). Besides annual and monthly means, also frequencies are presented, such as the occurrence of days with frost or with more than 10 mm precipitation. It should be noted that the model results are based on 10 years instead of the reference period of 30 years. The length of the experiments was restricted to save expensive computing time. It is realized that this restriction may lead to underestimation or overestimation of the frequency of extremes. However, it is assumed in this paper that the results of 10 years are sufficient to make a reasonable estimate of climate variability.

Modern climate: CTRL vs. measurements

Temperature

The model gives a reasonable representation of the present surface temperature, although it somewhat overestimates the mean summer temperatures. Figure 1a shows that CTRL produces values for May to August that are up to 1.4°C higher than any of the stations, causing the yearly average temperature also to be slightly higher (10.1°C compared to a range of 8.6 to 10.0°C). As noted earlier, these relatively high summer temperatures in W Europe are a known deficiency of the model (Roeckner et al., 1996). For September to April the model result falls within the range of values measured at the 5 stations, ranging from 2.8°C in January to 15.4°C in September. As shown in Table 2, the frequencies of events also correspond to observations. The frequency of "ice" days (mean daily temperature below 0°C) and of days with "severe" frost (minimum temperature below –10°C) corresponds with the measurements, as well as the occurrence of days with a maximum temperature reaching 25°C.

Wind speed

The simulated wind strength corresponds to data given for the five stations (Fig. 1b). For October to March, the model produces a wind speed regime that corresponds with the values of coastal stations (6 to 7 m/s). As noted for temperatures, the simulated wind conditions during summer appear less realistic, with wind speeds that are lower (4 to 5 m/s) than those for the coastal stations (6 m/s). The calculated frequency of high wind speed events – days with wind speed reaching 6 Bft or 10.8 m/s – is 9% (see Table 2), a value that is similar to that of the inland stations of Eelde (11%) and Beek (8%).

Precipitation, snowfall and effective precipitation (P-E)

The model clearly overestimates precipitation during January to March and produces an underestimation during July to November (Fig. 1c). The simulated anomalously low summer precipitation is a known model deficiency (see methods section and Roeckner et al., 1996). This underestimation during summer is not fully compensated for by the high winter values, so that the mean annual precipitation sum in CTRL is somewhat lower than observations (i.e., 698 mm opposed to a range of 731 to 802 mm). This comparison suggests that one should be cautious with the re-

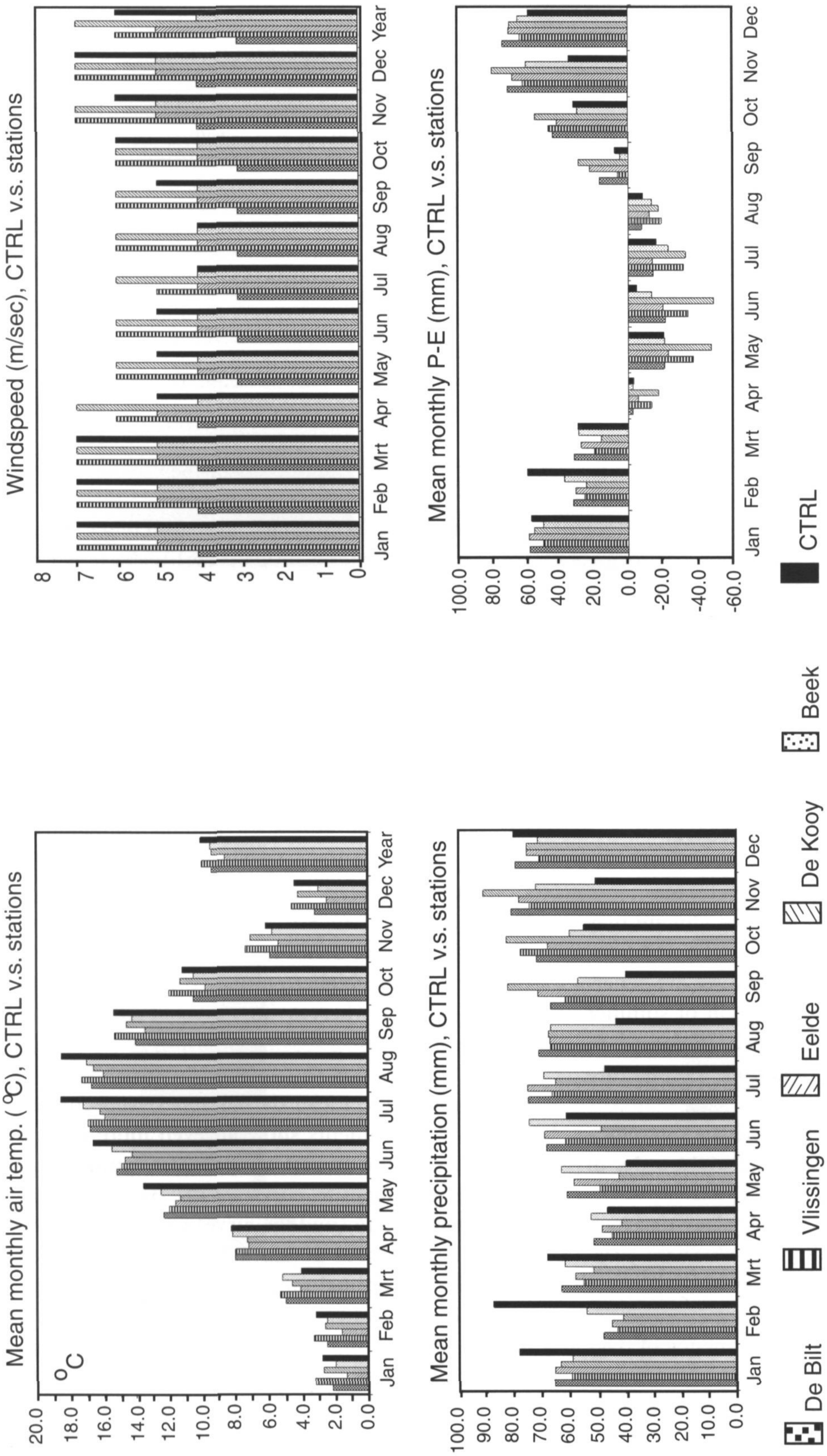

Figure 1a-d:
Mean monthly results for CTRL (based on 10 years, gridcell 'The Netherlands') and five stations (30 years, 1961-1990) in The Netherlands (Krijnen & Nellestijn, 1992). 1a: surface (2 m) air temperatures in °C, 1b: wind speeds (10 m) in m/s, 1c: precipitation in mm, 1d: precipitation minus evaporation in mm.

sults for monthly precipitation and that it is preferred to consider the yearly averages when analysing PBexp and YDexp. Moreover, the frequency of occurrence of days without precipitation (i.e. less than 0.1 mm, 27%) and with 10 mm or more (3%) is less in the model than observed (31 to 37% and 5 to 6% respectively, Table 2). However, the simulated frequency of days with snowfall (10%) is in agreement with the

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Table 2. Frequency of extremes for CTRL, PBexp, YDexp and five stations in The Netherlands (Krijnen & Nellestijn, 1992). The simulation results are based on 10 model years, whereas the station data are for the reference period 1961-1990. Please note that the frequencies are expressed as percentages to facilitate model-data comparison, since a model year consists of 360 days instead of 365.

	Days/yr Tmean < 0°C [%]	Days/yr Tmin < −10°C [%]	Days/yr Tmax ≥ 25°C [%]	Days/yr Wind sp. ≥ 6Bft (10.8m/s) [%]	Days/yr Precip ≥10 mm [%]	Days/yr with No Precip [%]	Days/yr with snowfall [%]
De Bilt	7	1	5	2	6	32	8
Vlissingen	4	0	2	29	5	37	6
Eelde	9	2	4	11	5	31	10
De Kooy	5	1	1	33	5	35	8
Beek	8	1	6	8	5	31	10
CTRL	5	0	4	9	3	27	10
PBexp	13	2	13	3	3	28	19
YDexp	38	16	1	12	2	13	41

values for the inland stations of Eelde and Beek (see Table 2). Despite the imperfect simulation of precipitation, most simulated monthly P-E values fall within the range of data provided for the five stations (Fig 1d). A surplus in effective precipitation is shown for the period September to March, whereas negative P-E values are recorded for April to August. The model overestimates the value for February, but underestimates values for June and November. The mean annual P-E sum (227 mm) falls in the range of the station estimates that vary from 138 to 260 mm.

Summary of model performance for modern climate

The model performance for the present climate may be summarised as follows:

- The mean monthly surface temperatures are generally well simulated, with the exception of summer temperatures that are overestimated compared to station data. The frequency of certain temperature extremes is also well reproduced.
- The mean monthly wind speeds and the frequency of high wind-speed events are of the right order of magnitude.
- The mean annual precipitation is slightly underestimated; the monthly precipitation values are overestimated during winter and underestimated during summer.
- The amount of snowfall and the frequency of days with snowfall match with observations.
- The monthly and annual mean P-E values generally correspond with station estimates.

PB and YD climates

Temperature

A comparison of the mean monthly temperatures of the three experiments reveals significant differences. In PBexp, the seasonality (i.e. difference between summer and winter season) seems to be larger compared to CTRL (see Fig. 2a). The mean monthly temperatures of the winter half year (October to March) are substantially lower (January temperature −0.1°C and max. PBexp-CTRL difference 3.3°C), whereas the summer values are higher than in CTRL, reaching 21.0°C in July (max. PBexp-CTRL difference 2.4°C). However, as the anomaly for the summer half year is somewhat smaller than for winter, the net result is that the mean annual temperature is slightly lower in PBexp (only 0.4°C) than in CTRL. Compared to PBexp, the mean monthly temperatures for YDexp are 5 to 8°C lower throughout the year. The difference in mean annual temperatures is 7°C. In summer, the highest monthly value in YDexp is 14.1°C (July), whereas in winter it goes down to −8.2°C (January).

As expected, the mean daily temperature curves for the three experiments show an even more expressed difference in the annual temperature range than the monthly temperature curves (Figs. 3a-c). The mean daily temperature (middle curve) represents the average of 10 values, as 10 annual cycles are considered. In CTRL the annual range in average daily temperature is 19.8°C, whereas in PBexp and YDexp the values are 25.3°C and 31.6°C respectively. Besides the mean daily values, also the minimum and maximum daily temperatures are plotted in Figure 3 to give an impression of the inter-annual range in mean daily temperatures. Please note that these minimum and maximum values are the extremes of the *mean* daily temperatures and differ from the absolute minimum and maximum temperatures. The difference between the minimum and maximum curves is in the summer half year typically in the range of 4 to 8°C. In all ex-

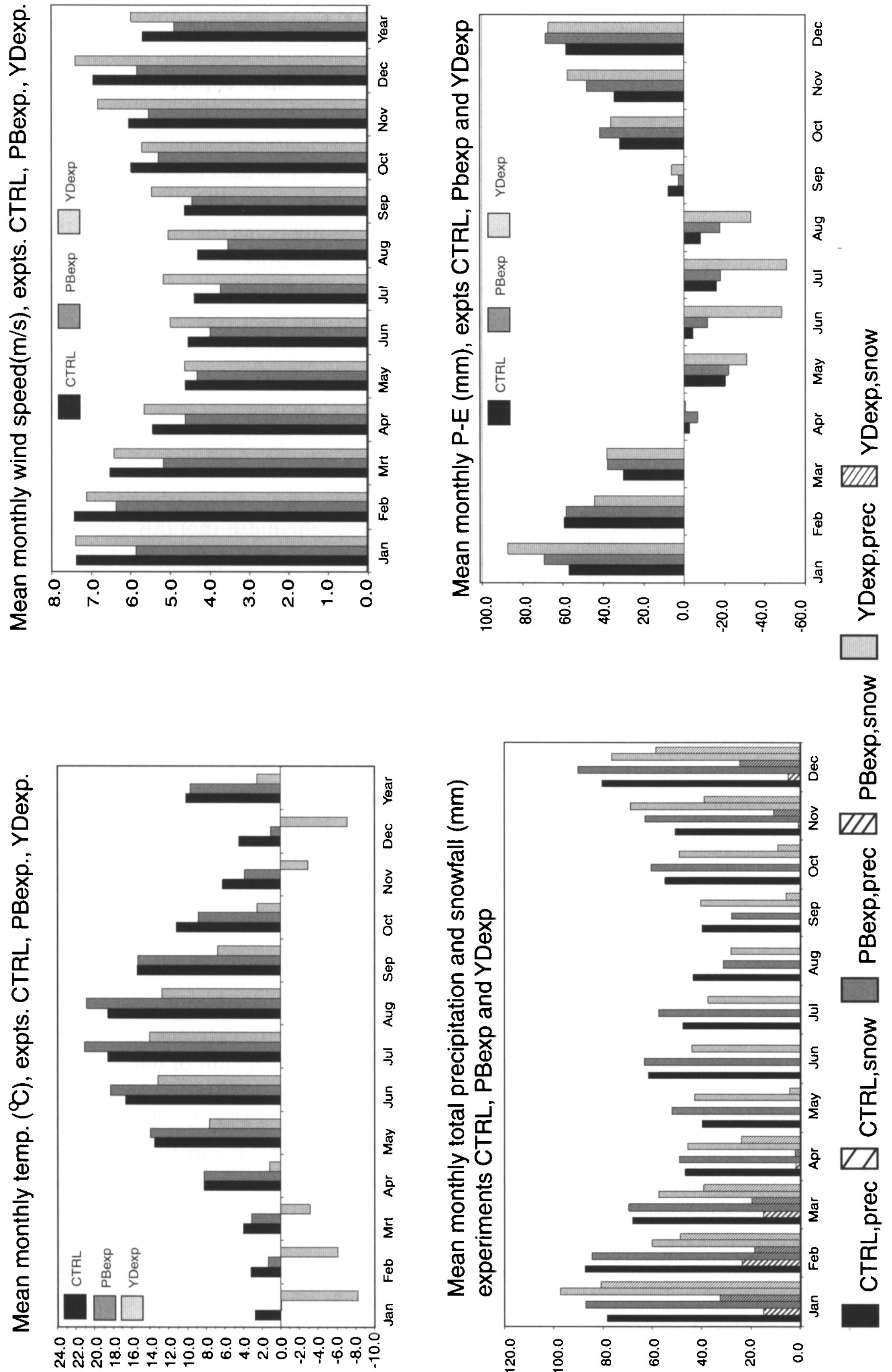

Figure 2a-d:
Mean monthly results for CTRL, PBexp and YDexp (based on 10 years, gridcell 'The Netherlands'). 2a: surface (2 m) air temperatures in °C, 2b: wind speeds (10 m) in m/s, 2c: precipitation in mm, 2d: precipitation minus evaporation (P-E) in mm.

periments, this difference between the extreme curves is larger during winter, revealing more inter-annual variability. However, the curves for YDexp show a marked inter-annual variability for winter that exceeds that of PBexp considerably. For instance, for some days in January a mean daily temperature of +2°C is simulated in one year (upper curve Fig. 3c), while in another year it is below –40°C (lower curve). An analysis of the 'raw' results shows that also a strong day-to-day variability is involved, as in many cases the daily temperatures jump within a few days from –30°C to +1°C. This analysis has also shown

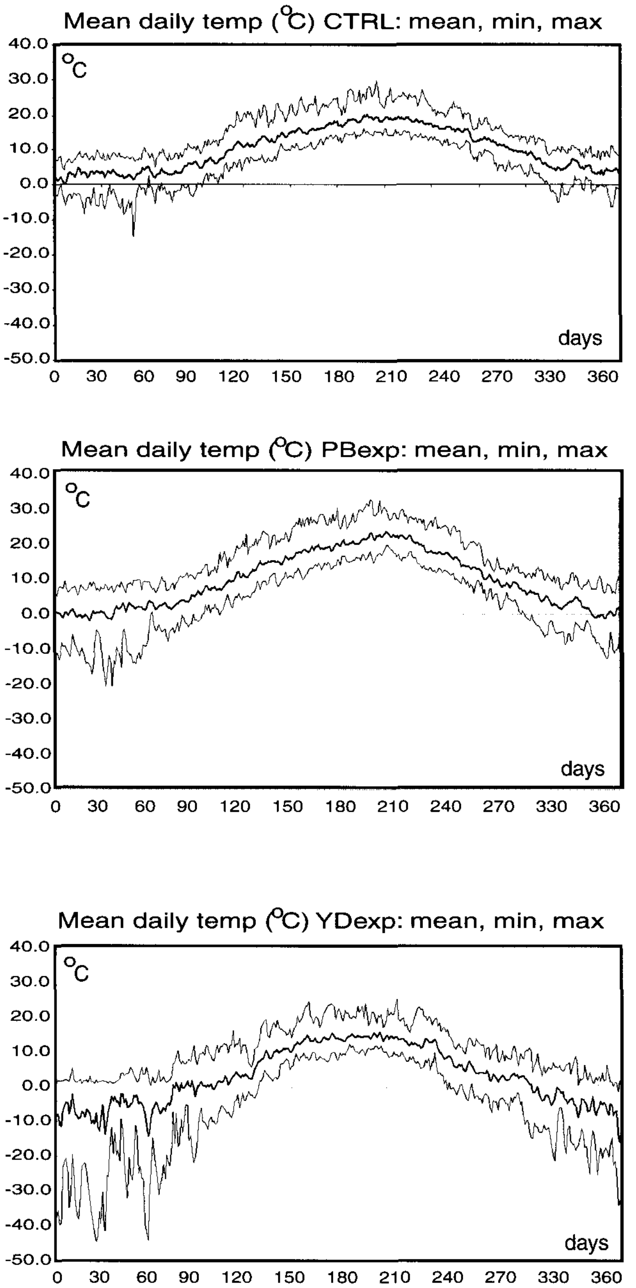

Figure 3a-c:
Annual cycle of mean daily temperatures (bold middle curve, mean of 10 days) and extremes: minimum (lower curve) and maximum (upper curve), values of days out of 10 with lowest or highest mean daily temperatures. 3a) CTRL, 3b) PBexp, 3c) YDexp.

that the variability is probably associated with the passage of depressions, as the jumps in temperature are accompanied by increases in precipitation. During the passage of a depression, the source region of the air masses changes, as typically just before a depression relatively warm and moist air is transported with SW winds from the ice-free Atlantic towards Europe. This warm and moist flow interrupts the transport of cold and dry air originating from the (partly) ice covered northernmost Atlantic Ocean and Nordic seas. An analysis of day-to-day variability of wind direction has revealed that the frequency of cold easterly winds is lower in YDexp compared to PBexp and CTRL (not shown).

The simulated frequency of extreme events (Table 2) in YDexp and PBexp supports the notion of a well-expressed temperature difference for the YD and PB climatic regimes. Compared to YDexp, the occurrence of days with frost (mean temperature < 0°C) and with 'severe' frost (minimum temperature < –10°C) is in PBexp reduced by 25% and 14% respectively. On the other hand, the frequency of days with maximum temperatures of 25°C or more increases substantially (+12%).

Winds
Throughout the year, the mean monthly wind speeds are substantially lower in PBexp than in CTRL and YDexp (Fig. 2b). Compared to YDexp, the mean difference is more than 1 m/s, implying that on average winds in YDexp (yearly mean 6.0 m/s) are about 20% stronger than in PBexp (yearly mean 4.9 m/s). The difference in wind climate between the two experiments is also expressed in the frequency of days with wind strength reaching 6 Bft (i.e. 10.8 m/s), which is 3% in PBexp and 12% in YDexp (compared to 9% in CTRL, see Table 2). In YDexp, the winds are relatively strong during summer (when minimum values are found for CTRL and PBexp) and resemble what is seen during autumn in CTRL. The minimum mean monthly wind speeds in YDexp are recorded in May (4.6 m/s).

Precipitation, snowfall and P-E
Compared to CTRL (annual sum of 698 mm), more precipitation is simulated in PBexp (735 mm) and less in YDexp (647 mm, see Fig. 2c). This implies an increase in precipitation of 14% in PBexp compared to YDexp. In addition, as shown in Table 2, the frequency of days with ≥10 mm precipitation is slightly less in YDexp (2%) than in PBexp (3%). However, in YDexp the precipitation seems to be more evenly distributed over the year, as the number of days without precipitation (13%) is substantially lower than in PBexp (28%). As expected from the simulated temperature regimes, snowfall is in both PBexp and YDexp much more common than in CTRL (see Fig 2c). Nearly half of the simulated precipitation (48%) in YDexp falls as snow (i.e. 308 mm). In PBexp this percentage is still 15% (107 mm), compared to 9% in CTRL (61 mm). Moreover, the frequency of days with snowfall observed in CTRL (10%) is nearly doubled in PBexp (19%) and quadrupled in YDexp

(41%, see Table 2). In the latter experiment snowfall is only absent from June to August (Fig. 2c). The trend in simulated P-E is the same as noted for the precipitation, as – compared to CTRL – the values are higher in PBexp and lower in YDexp. The yearly sums are as follows: 227 mm (CTRL), 251 mm (PB-exp) and 173 mm (YDexp). Consequently, the YD-exp-PBexp difference in P-E (45%) is much more substantial than in precipitation (14%). This can be attributed to the distinct negative P-E values simulated in summer in YDexp (see Fig. 2d).

Discussion and conclusions

The presented simulations suggest the following changes in climate during the YD-PB transition in The Netherlands:

- An increase in monthly temperatures ranging from 5 to 8°C and in mean annual values of 7°C.
- A decrease in the annual range of mean daily temperatures (in the model from 31.6°C in YDexp to 25.3°C in PBexp).
- A 20% reduction in monthly mean wind speed and a four-fold decrease in the frequency of strong wind events.
- An increase in mean annual values of precipitation (14%) and effective precipitation (more than 40%).
- More frequent heavy rain events and a doubling of the number of days without precipitation. In other words, in PB more precipitation is falling in fewer days.
- A strong decrease in the amount of snowfall (more than 60%) and a 50% reduction in the frequency of days with snowfall.

To what extent are these changes realistic?

One could argue that the YDexp-PBexp difference is not seriously biased by model deficiencies, at least if it is assumed that the errors described for CTRL (sect. 3.1) are equally present in YDexp and PBexp (cf. Isarin & Renssen, 1999). Accepting this assumption still leaves uncertainties related to the prescribed boundary conditions. Therefore, it is very useful to evaluate the validity of the simulated changes by reviewing their consistency with proxy records.

A comparison of simulated temperatures with reconstructions in an earlier study suggested that the YD winters and PB summers in The Netherlands were colder than suggested by YDexp and PBexp (Renssen & Isarin, 2001). The results for the YD summers and PB winters were similar in model results and reconstructions. Proxy data suggest for the YD a mean winter temperature of –20°C for The Netherlands as opposed to –7°C to –8°C in YDexp. The model-data mismatch was explained by the position of the sea-ice margin, as this was probably located at 52°N instead of the 55-60°N prescribed in YDexp (Renssen & Isarin, 1998). This is supported by a simulation with Late Pleni-glacial boundary conditions (including an expanded winter sea-ice cover at 50°N) that produced winter temperatures of –20°C in NW Europe (Renssen & Isarin, 2001). As a consequence, the winter temperature increase over the YD-PB transition was probably at least twice the suggested 8°C. Moreover, it is most likely that the amount of snow fall is also underestimated, since in YDexp still a small proportion of the winter precipitation is falling as rain (see Fig. 2c). Assuming that the YD winter temperatures were much lower than the simulated –7°C to –8°C, it is likely that in the YD most precipitation in November to April was in the form of snow, so that a snow pack was covering the surface during half of the year. Consequently, probably the amount of snowfall decreased even more over the YD-PB transition than the simulated 60%. On the other hand, since evaporation was lower during YD winters than suggested by the anomalously warm YDexp, the difference in P-E sum between YD and PB is probably lower than the 40% increase suggested by the model (assuming that precipitation is reasonably simulated). The reconstructions based on proxy data suggest that PBexp overestimates PB summer temperatures in The Netherlands by 1 to 2°C. In short, probably the increase in summer temperatures over the YD-PB transition is less than the simulated 5°C, whereas the increase in winter temperatures is more than suggested by the experiments.

The simulated increase in precipitation and P-E is in agreement with the inferred rise in lake levels during the early PB (Bohncke & Wijmstra, 1988; Bohncke, 1993). Moreover, the calculated decrease in wind strength and in frequency of high wind speed events is consistent with the decrease in aeolian activity inferred for the YD-PB transition (e.g., Vandenberghe, 1991; Kasse, 1995). It should be noted that proxy data suggest that the YD may be divided in an earlier wetter part and a drier second part (e.g., Bohncke et al., 1988; 1993; Bohncke and Vandenberghe, 1991; Vandenberghe, 1995; Renssen et al., 2000b). Moreover, the early PB is also subdivided by palaeo-ecologists in the Friesland (relatively warm) and Rammelbeek (relatively cold or continental) phases (e.g., Wijmstra & de Vin, 1971; van Geel et al., 1980/1981). However, as already noted, the relatively poor temporal resolution of the boundary conditions did not enable us to make these distinctions.

Are the simulated changes consistent with prescribed boundary conditions?

The two most important boundary conditions are insolation and the state of the ocean surface. The large increase in seasonality in PBexp compared to CTRL can be attributed to insolation changes. As mentioned earlier, the insolation values were very different from today, with higher values during summer (more than 30 W/m^2 difference) and lower values during winter (about 10 W/m^2 difference) (Berger, 1978). The model response in PBexp is similar to results of simulations in which only the insolation of 6 cal ky BP was changed compared to today (e.g., Texier et al., 1997). The prescribed insolation in YDexp is not very different from that in PBexp, suggesting that other boundary conditions were the main driving factors behind the YDexp-PBexp anomalies. The most important difference between the two experiments is the state of the N Atlantic Ocean, as the change in other boundary conditions was relatively small (see Table 2). In PBexp the ocean surface conditions are equal to those in CTRL, whereas in YDexp the Atlantic was cooled by more than 8°C, leading to a sea-ice cover north of 55-60°N in winter. This sea ice cover enhanced the seasonality in YDexp even further. In winter, the air cooled to temperatures below –35°C over the sea-ice cover (i.e. >30°C difference compared to CTRL), whereas in summer the ocean was ice free up to 70°N with SSTs 8°C lower than today (Renssen, 1997). This strong seasonal contrast was also experienced in W Europe, as during the YD a westerly atmospheric circulation was prevailing (Renssen et al., 1996; Isarin et al., 1997). Moreover, the strong cooling over the extended sea ice steepened the meridional temperature gradient, causing an intensification of the westerlies in YDexp. This explains the noted relatively high wind speeds in YDexp. In PBexp, relatively weak winds are simulated, even compared to CTRL. This difference that may be attributed to the more continental setting of The Netherlands in PBexp. The roughness length (i.e. resistance experienced by air flow) is much larger over land surfaces than over the oceans, causing the winds to be stronger in The Netherlands in CTRL than in PBexp due to the vicinity of the North Sea in the former experiment (cf. Isarin et al. 1997).

What caused the YDexp-PBexp changes in precipitation and P-E? Renssen et al. (1996) have shown that in winter the main depression track was displaced southward from about 60°N (today) to 55°N (YD), following the main temperature gradient along the sea ice margin. Together with the strengthening of the westerlies, this would bring more frequently depressions towards W Europe in YDexp than in PBexp. However, in YDexp lower precipitation values are simulated despite these more frequent depressions. This may be explained by the fact that in YDexp a substantial part of the Atlantic Ocean was not available as a moisture source because of the extended sea ice cover. Moreover, the low temperatures in YDexp lowered the moisture-holding capacity of the air. Consequently, the latter two factors caused the air to be relatively dry in YDexp compared to PBexp. The parameterisation of permafrost applied in YDexp influenced the P-E fluxes substantially. Part of this parameterisation is the constant high ground water table in areas with permafrost (including The Netherlands), providing an unlimited moisture source in summer (Renssen et al., 2000a). The latter effect produced, together with the relatively strong winds, high evaporation values in YDexp, explaining the strong negative P-E fluxes in summer in Figure 2d.

Concluding remarks

Our model suggests the following characteristics for the YD and PB climates in The Netherlands. The YD climate is characterised by cold winters (daily temperatures frequently under –20°C) under influence of the sea-ice covered N Atlantic, whereas the summers were already quite mild (daily temperatures over 13°C) because of the relatively high insolation values. Furthermore, a strong interannual and day-to-day variability is simulated with strong fluctuations of temperatures, frequent storms and snowfall from September to May. The inferred YD temperature regime is today found in northern Russia, for example in Nar'yan Mar (Pechora delta, 67°39'N, 53°01'E), with mean annual, January and July temperatures of –3.9°C, –17.3°C and 12.0°C, respectively (Lydolph, 1977). However, at this location the climate is much drier, with an annual precipitation sum of only 378 mm. The PB climate was a 'continental' version of present climate, with warmer summers and cooler winters (~2°C difference in both seasons compared to today), more snowfall, but lower wind speeds. In addition, the PB climate was probably wetter than the present climate. Today, a similar climate is found in eastern Europe, for example in Simferopol (Southern Ukraine, 45°01'N, 33°59'E) with mean annual, January and July temperatures of 9.8°C, –0.7°C and 20.6°C, respectively, and an annual precipitation sum of 768 mm (Lydolph, 1977). Considering that the transition between these very different climates occurred within 50 years, it is indeed expected that the changes had a large impact on the environment in The Netherlands. Fortunately, these changes during the YD-PB transition are incomparable to the gradual and small climate changes that we are experiencing today.

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