FUTURE CLIMATIC CHANGES: ARE WE ENTERING AN EXCEPTIONALLY LONG INTERGLACIAL?

M. F. LOUTRE and A. BERGER
Université catholique de Louvain, Institut d'Astronomie et de Géophysique G. Lemaître, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium

Abstract. Various experiments have been conducted using the Louvain-la-Neuve two-dimensional Northern Hemisphere climate model (LLN 2-D NH) to simulate climate for the next 130 kyr into the future. Simulations start with values representing the present-day Northern Hemisphere ice sheet, using different scenarios for future CO_2 concentrations. The sensitivity of the model to the initial size of the Greenland ice sheet, and to possible impacts of human activities, has also been tested. Most of the natural scenarios indicate that: (i) the climate is likely to experience a long lasting (∼50 kyr) interglacial; (ii) the next glacial maximum is expected to be most intense at around 100 kyr after present (AP), with a likely interstadial at ∼60 kyr AP; and (iii) after 100 kyr AP continental ice rapidly melts, leading to an ice volume minimum 20 kyr later. However, the amplitude and, to a lesser extent, the timing of future climatic changes depend on the CO_2 scenario and on the initial conditions related to the assumed present-day ice volume. According to our modelling experiments, man's activities over the next centuries may significantly affect the ice-sheet's behaviour for approximately the next 50 kyr. Finally, the existence of thresholds in CO_2 and insolation, earlier shown to be significant for the past, is confirmed to be also important for the future.

1. Introduction

Future climate on geological time scales is still a topical question, mainly because of two major problems that society has to face: (i) the choice of suitable repository sites for nuclear waste disposal (Goodess and Palutikof, 1991; Goodess et al., 1992) and (ii) the intensification of the greenhouse effect by man's activities (Houghton et al., 1996). Since the working Conference of 1972 (Kukla et al., 1972), scientists tried to predict probable future climate trends over the next millennia from analogs in the records of past interglacials and the immediately post-interglacial intervals. Paleoclimatic evidence lead to an estimate of the length of the last three interglacials of about 10 kyr each, although recent analyses tend to conclude that the last interglacial must have been twice as long (Kukla et al., 1997; Winograd et al., 1997). Assuming that the duration of the current warm period is similar in length to the last interglacials, the 1972 workshop predicted that 'it is likely that the present-day warm epoch will terminate relatively soon if man does not intervene'. But there may be no warm time period that is a satisfactory past analog for future climate, because the mechanisms producing such warm periods in the past may have been totally different from those occurring now (Crowley, 1990; Mitchell, 1990). Both the insolation and the greenhouse forcing can already differ considerably from one

Climatic Change **46:** 61–90, 2000.

period of geological time to another, which is particularly true if the Holocene and the Eem interglacials are considered.

Unfortunately, only limited attempts have been made to tentatively predict Earth's future climate at geological time scales on a quantitative basis. Some of these experiments – the first ones dating from the early 1970s – were based upon statistical rules for projecting the past into the future (Mitchell, 1972; Berger et al., 1991 for a review). They predicted a slow cooling trend starting 6000 YBP (Berger et al., 1990c), this cooling being now observed in the Greenland temperature record (Johnsen et al., 1995), a cold interval around 25 kyr AP and a glaciation around 55 kyr AP. This glaciation might be delayed until after 70 kyr AP (Ledley, 1995). All these predictions implicitly assumed a CO_2 constant as this variable was not explicitly used as a predictor in the multiple variable regression used. The impact of such a failure will be shown later on in this paper. Other experiments were oriented more toward a modeling approach (Berger, 1995; Adem, 1996) including the possible effects of anthropogenically increased CO_2 on the dynamics of the ice age cycles. Saltzman et al. (1993) concluded that if values of CO_2 higher than 350 ppmv were to become established, the climate system would be placed into a stable non-oscillating regime characterised by low ice mass and perhaps by a retreat of the Greenland and Antarctic ice sheets. To understand the impact of a possibly warmer future climate, geologists are also searching the past for warmer-than-present interglacial intervals (Howard, 1997).

In the late 1980s, the LLN coupled climate model began to be used for discussion of the climate of the next millennia, including the possible impact of man's activities (Gallée, 1989; Loutre, 1995). This paper reports results obtained concerning (i) the very peculiar astronomical forcing, almost unique, which characterises the present and the next tens of thousands of years; (ii) modeling experiments using different CO_2 scenarios, constant or variable, both at the geological and at the human time scales; and (iii) the possible impact of man's activities during the next centuries on climate evolution at millennia time scales.

2. Modelling Long-Term Climatic Variations

Quaternary studies provide evidence that past climate changes are largely driven by the Earth's orbital changes. It is now recognised that present-day climate and characteristics of the Earth's surface (ice-sheet extent, vegetation cover, etc.) represent a possibly short interglacial within the last climatic cycle, which was dominated by glacial conditions. Such glacial-interglacial cycles will presumably be repeated in the future. This possibility can only be investigated through simulations of future climate based on scenarios for the external forcing and anthropogenic effects. In addition to General Circulation Models which provide useful results for the next centuries to a few millennia (Cubasch et al., 1992; Hasselmann et al., 1995; Manabe and Stouffer, 1994; Mitchell et al., 1995), the LLN 2-D climate model (Gallée et al., 1991, 1992) produces additional information by simulating the transient response of the climate system forced by both long-term variations in insolation and natural or anthropic CO_2 concentration over tens to hundreds of thousands of years. The quality of such predictions depends upon the reliability of the calculated external forcing and the quality of the model used.

The LLN 2-D model is altitude-latitude dependent. It links the Northern Hemisphere atmosphere, ocean mixed layer, sea ice, ice sheets and continents. In each latitudinal belt, the surface is divided into at most seven oceanic or continental surface types, each of which interacts separately with the subsurface and the atmosphere. The oceanic surface can be ice-free ocean or sea-ice covered, while the continental surfaces can be snow-covered or snow-free and include Northern Hemisphere ice sheets. Atmospheric dynamics is represented by a zonally averaged quasi-geostrophic model, which includes a parameterisation of the meridional transport of potential vorticity and a parameterisation of the Hadley sensible heat transport. The atmosphere interacts with the other components of the climate system through vertical fluxes of momentum, heat and water vapour. The model explicitly incorporates detailed radiative transfer, surface energy balances, and snow and sea-ice budgets. The vertical profile of the upper ocean temperature is computed using a mixed-layer model, which takes into account the meridional convergence of heat. A thermodynamic model including leads and a parameterisation of lateral accretion represents sea ice. Simulation of the present climate shows that the model is able to reproduce the main characteristics of the general circulation (Gallée et al., 1991). The seasonal cycles of the oceanic mixed layer, sea ice, and snow cover are also fairly well reproduced. The global mean temperature increase for doubling CO_2 concentration (from 330 ppmv to 660 ppmv) is $\sim 2\,^{\circ}$C. The atmosphere-ocean model is asynchronously coupled to a model of the three main Northern Hemisphere ice sheets and their underlying bedrock. Since the model does not contain any representation of the carbon cycle, the atmospheric CO_2 concentration is considered as an external forcing in addition to the astronomically derived insolation.

Many experiments have been made to validate this coupled climate model, for describing the whole Quaternary. The model is able to simulate long-term variations of the Northern Hemisphere ice volume using either a constant CO_2 value (Berger et al., 1998a) or a CO_2 record as reconstructed from Vostok (Jouzel et al., 1993) or from deep-sea cores (Shackleton et al., 1992). The model also simulated successfully the initiation of glaciation at around 2.75 Myr BP (Li et al., 1998a), the late Pliocene-early Pleistocene 41-kyr cycle, the emergence of the 100-kyr cycle around 900 kyr BP, the glacial-interglacial cycles of the middle and late Pleistocene (Berger et al., 1998b) and the importance of CO_2 in shaping the climate of isotopic stages 11 and 1 (our present Holocene interglacial; Li et al., 1998b).

Hays et al. (1976) demonstrated that the orbital forcing acts as a pacemaker for the ice ages over the last 200 kyr. This was confirmed by the LLN modelling experiments (Berger et al., 1990a; Gallée et al., 1992), showing that variations in the Earth's insolation alone are sufficient to induce feedbacks in the climate system (Berger et al., 1990b) which amplify the direct radiative impact and generate large climatic changes. In particular, CO_2 was shown to play an important role in the amplification of the climatic response to orbital forcing (Lorius et al., 1990, 1993; Berger et al., 1993a). Others are water-vapour feedback (Berger et al., 1993a), albedo-temperature feedback (in particular related to the snow covered taiga versus tundra in high polar latitudes), altitude and continental effects on the snow precipitation over the ice sheets, the snow ageing process, and isostatic rebound (Berger et al., 1992, 1993b).

Because of its ability to simulate the past climate, the LLN 2-D model is used for the first time to simulate the climate of the next 130 kyr. Since the long-term variations of insolation are well established at that time scale (Berger and Loutre, 1991), the hypothetical variations in the scenarios will concern only the chemical composition of the atmosphere and, in particular, the concentration of CO_2 (and possibly other greenhouse gases). Sensitivity analyses of the model response to perturbations induced by human activities will also be conducted.

3. Past Insolation as an Analogue for the Future

The major characteristic features of the calculated insolation for the next 130 kyr are the small amplitude of its variations (Figure 1). For example, the amplitude of the long-term variations in mid-month insolation at 65° N in June increases slightly with time, but barely reaches 65 Wm^{-2} at the end of the interval. This is far less than the amplitude at stage 5 (110 Wm^{-2}). Moreover, from 0 to 50 kyr AP, this amplitude is even less than 30 Wm^{-2}. Consequently, considering insolation only, the Eemian can not be taken as an analogue for the next several thousand years, although it is often assumed that it can be.

This insolation variation from 5 kyr BP to 60 kyr AP is really exceptional, and has very few analogues in the past (Berger and Loutre, 1996). Over the last 3 Myr, only five intervals were found to be highly correlated to this reference insolation pattern (correlation coefficient higher than 0.8). They are (Figure 2): 405 to 340 kyr BP, 782 to 717 kyr BP, 1561 to 1496 kyr BP, 2016 to 1951 kyr BP, and 2867 to 2802 kyr BP. Mean insolation values are about the same for these 5 intervals ($\sim$487 Wm^{-2}) and the standard deviation ranges from 12 Wm^{-2} for the last interval to 16 Wm^{-2} for the third one (against 9 Wm^{-2} for the reference). Assuming that the insolation is the main driving force for the climate system, the best and closest analogue for our near future climate is the climate some 400 kyr BP. This interval corresponds to the interglacial oxygen isotope stage 11 in the stacked marine δO^{18} from SPECMAP (Imbrie et al., 1984).

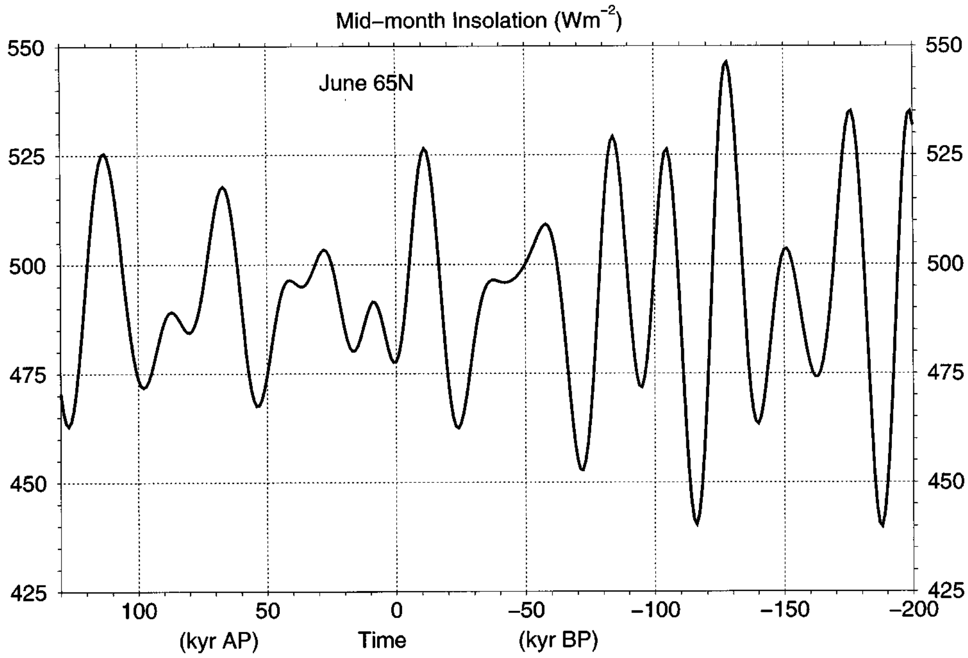

Figure 1. June mid-month insolation at 65° N over the last 200 kyr and the next 130 kyr (Berger, 1978).

4. Response to the Astronomical Forcing under Constant CO_2

4.1. THE FUTURE OF OUR CURRENT INTERGLACIAL, STARTING THE INTEGRATIONS WITH PRESENT-DAY CONDITIONS

For the last 200 kyr, ice volume changes simulated using three constant CO_2 concentrations (210, 250, 290 ppmv) show similarities as well as significant differences in the amount of simulated ice and in the timing of the glacials and interglacials (Berger and Loutre, 1997; Berger et al., 1998a). These experiments reveal that the sensitivity of the simulated climate to CO_2 concentration is time dependent. The best agreement with SPECMAP is obtained when a 210 ppmv CO_2 forcing is used (Berger et al., 1998a; Berger and Loutre, 1998).

Similarly experiments were performed to simulate the response of the climate model to insolation forcing for the next 130 kyr. Nine constant values for CO_2 concentration were used, ranging from 210 to 290 ppmv. We stress that the results shown in Figure 3 are obtained starting the integration with present-day conditions for the ice sheets and the lithosphere beneath. Present-day conditions over the North American, Greenland and Eurasian ice sheets (Figure 4) are actually obtained from a transient simulation of the last 200 kyr climate, forced by both variable insolation and CO_2 variations based on the Vostok record and ending today with the best representation of the current climate system.

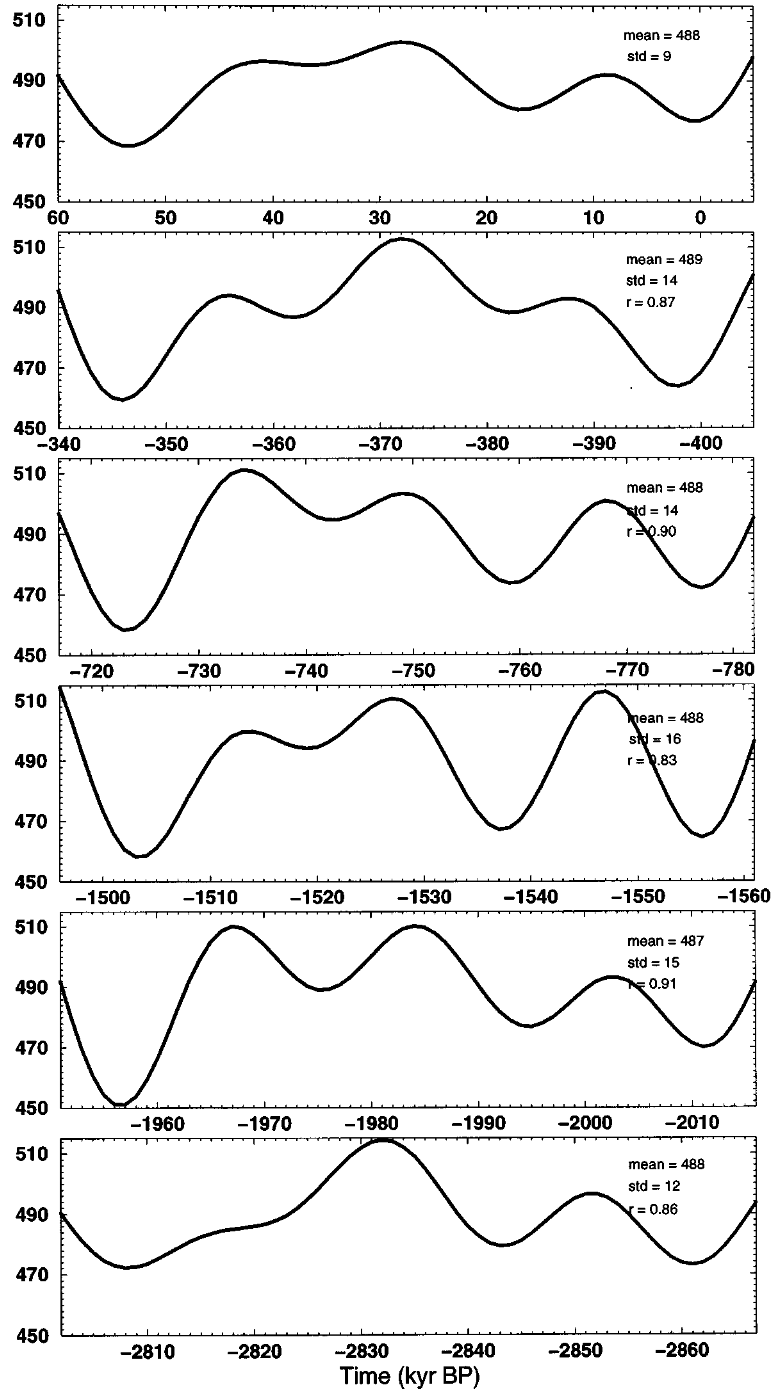

Figure 2. Mid-June insolation at 65° N for 6 periods of time belonging to the last 3 Myr and which are highly correlated to the reference series going from 5 kyr BP to 60 kyr AP.

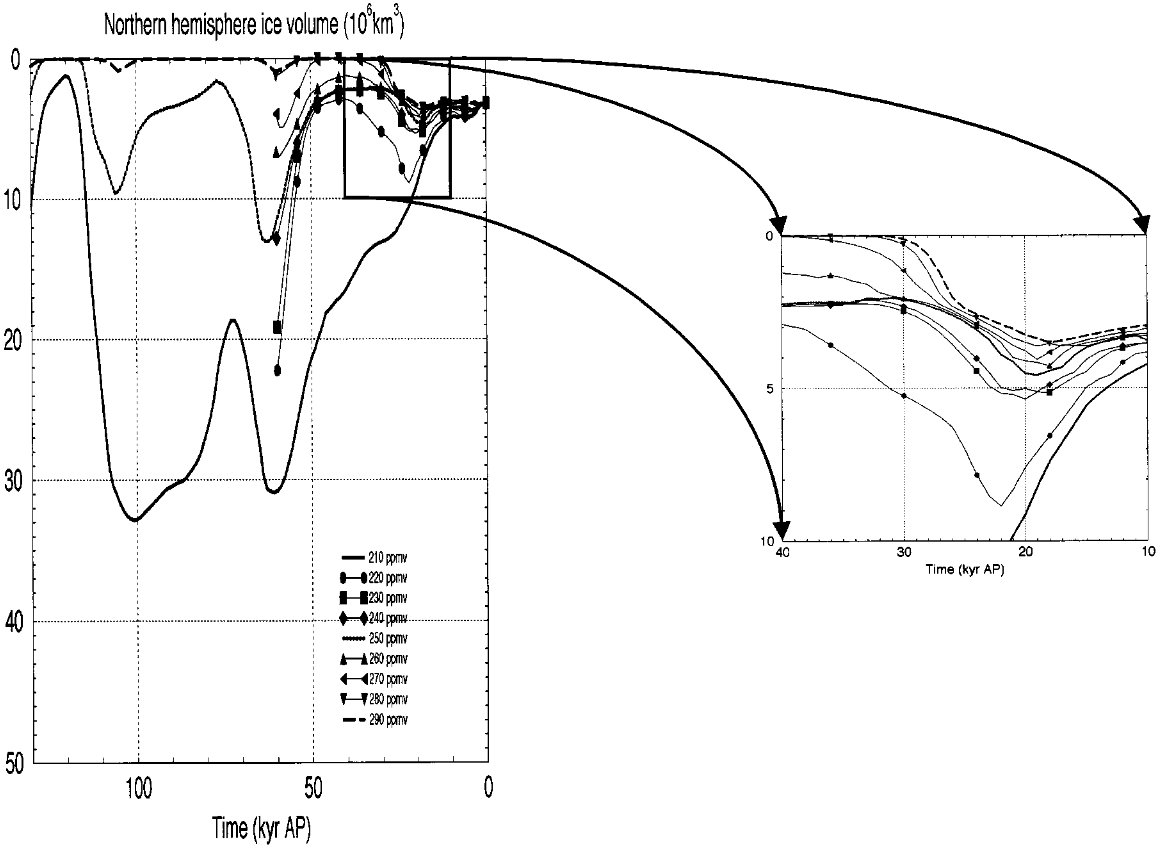

Figure 3. Simulated ice volume of the Northern Hemisphere using the LLN 2-D NH climate model forced by insolation and different constant CO_2 concentrations (from 210 ppmv to 290 ppmv). The integrations start with present-day conditions for the ice-sheets (3.2×10^6 km^3 of ice) and the present-day bedrock depression. (a) Over the next 130 kyr, (b) enlargement from 10 to 40 kyr AP.

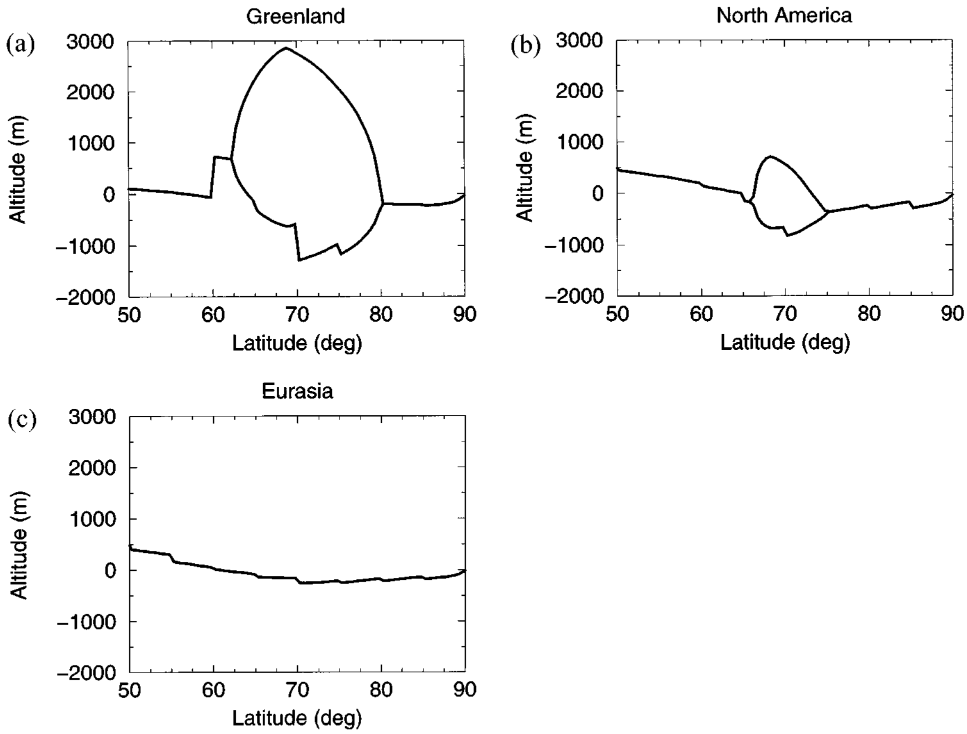

Figure 4. Latitudinal profiles of the crest elevation of the Northern Hemisphere ice sheets ((a) Greenland, (b) North America, and (c) Eurasia) used as initial boundary conditions for the simulations shown in Figure 3. They correspond to the best simulation of the present-day ice volume.

In all constant CO_2 scenarios, the simulated ice volume is barely influenced by the small insolation changes that characterise the next tens of thousands of years (Figure 3). However, over the following 15 kyr the response of the model starts to depend strongly upon the CO_2 concentration. For all concentrations larger than 230 ppmv, the simulated ice volumes remain close to each others and do not vary much. In contrast, with CO_2 level at 210 ppmv, ice volume increases more or less steadily from the present-day 3.2×10^6 km^3 to 5.5×10^6 km^3 at 15 kyr AP.

In response to insolation minimum at 17 kyr AP, ice volume increases for all simulations. It reaches a maximum for a CO_2 of 220 to 290 ppmv, but increases continuously in the 210 ppmv experiment. The maximum simulated under large CO_2 values, leads those simulated under lower CO_2 concentration and the amplitude of this cool event is CO_2-dependent. In response to the insolation maximum at 28 kyr AP, the ice sheet melts (partially or totally depending upon the CO_2 concentration) except for the 210 ppmv simulation.

The insolation reaches a value lower than the present-day level for the first time at 54 kyr AP. The timing, the amplitude and the increasing rate of the ice volume in response to the insolation forcing remain strongly dependent on CO_2.

The 210 ppmv experiment differs from the others in having a constantly increasing ice volume, reaching a maximum of more than 30×10^6 km^3 at 61 kyr AP. This ice buildup is more rapid from 15 kyr AP to 45 kyr AP, with an average accumulation rate of 0.56×10^6 km^3 per thousand years, than from the present-day to 15 kyr AP with an average of 0.27×10^6 km^3/kyr. The maximum of continental ice volume at 61 kyr AP is followed by a significant melting leaving less than 22×10^6 km^3 of ice at 72 kyr AP. The Next Glacial Maximum peaks at 101 kyr AP and is followed by a very large melting that culminates with the next interglacial at 120 kyr AP.

For CO_2 concentrations larger than 210 ppmv, the ice volume starts to increase again only after 35 to 50 kyr AP, according to the CO_2 concentration, in response to the insolation decrease after the 28 kyr AP maximum. In the 250 ppmv-experiment, the two main ice maxima are slightly delayed compared to the 210 ppmv-experiment and are much smaller. For all CO_2 larger than 250 ppmv, the ice sheets are completely melted from 115 kyr AP to 128 kyr AP.

These experiments illustrate important features of the response of the climate model to insolation under a constant CO_2 forcing. First, except for 210 ppmv, the present interglacial is quite stable and lasts longer than past interglacials. Its length is estimated to be about 55 kyr, compared with about or less than 30 kyr for previous interglacials (Kukla et al., 1997; Winograd et al., 1997). According to Broecker (1998) the periods of extreme warmth [the interglacials] appear to be roughly one half of a precession cycle (i.e., $\sim$11,000 yr). However, the duration of the marine isotope stage 11 was considerably longer according to Oppo et al. (1998). If stage 11 is taken as an analogue for the present interglacial, this last can still continue for a few thousand years. In our simulations, defining an interglacial as the time interval during which the amount of continental ice is smaller than 6×10^6 km^3, their maximum length during the last 200 kyr appears to be 25 kyr. Second, at about 20 kyr AP, the sensitivity of the model to CO_2 starts to be the same as for intervals of the past when the Earth had little glaciation. Similar to isotopic stage 5c (some 100 kyr ago), the response of the model to a 250 ppmv forcing is much closer to the response to a 290 ppmv concentration than to the 210 ppmv one. Third, in the interval from 0 to 50 kyr AP, during which the amplitude of the insolation variation is small, only a CO_2 level of 210 ppmv is able to drive the system into an ice age. Such a sensitivity persists over the whole interval up until 100 kyr AP, whereas it was limited to much shorter periods during isotopic stage 5. Fourth, the ice maximum at about 60 kyr AP suggests that there is an insolation threshold that must be crossed before the ice volume is able to increase to a significant amount. This threshold is CO_2 dependent: it is already reached with the present-day value of 480 Wm^{-2} at 65° N in June for 210 ppmv; it is probably only slightly below this value for 220 ppmv, but it is about 470 Wm^{-2} for CO_2 values larger than 260 ppmv. This CO_2-dependency of the insolation threshold can be better viewed as a history-dependency of climatic change. Indeed, in the 210 ppmv-experiment, the decrease of insolation from 496 Wm^{-2} at 41 kyr AP to 467 Wm^{-2} at 54 kyr AP occurs while the amount of ice is already large in the Northern Hemisphere

(17×10^6 km^3 at 41 kyr AP). This is not the case for CO_2 concentrations larger than 250 ppmv. Therefore, the subsequent albedo-temperature feedback in the low CO_2 experiments explains the strong response of the model to this insolation change.

In other words ice volume variations against CO_2 concentration is showing a hysteresis behaviour. Our model thus confirms this property of the climate already described for the glacial cycles (Saltzman and Verbitsky, 1994), for the Greenland ice sheet (Crowley and Baum, 1995) and for the ocean thermohaline circulation (Stocker and Wright, 1991; Mikolajewicz and Maier-Reimer, 1994; Rahmstorf and Ganopolski, 1999). CO_2 concentration must fall below some threshold before large ice sheets start to form. However, large ice sheets melt only slightly when CO_2 increases. It is only when it becomes already large that they rapidly melt. The existence of a CO_2-threshold value between 230 and 240 ppmv is confirmed by the steep acceleration toward the ice maximum of $\sim$60 kyr AP in the 230 and 220 ppmv experiments as opposed to what happens under a CO_2 forcing of 240 ppmv and above. This threshold value is very close to the average atmospheric CO_2 concentration of the last 200 kyr. Thus we suggest (see also Berger et al., 1998b) that, in the case of a cold-glaciated Earth, large CO_2 values are required to counterbalance the surface conditions, while in the case of a warm-ice-free Earth low CO_2 values are required to enter into glaciation. This history-dependency of climatic change is even stronger when insolation changes are not large enough to drive the climate system. Still because of the small insolation variation over the next 100 kyr, the melting of the ice sheets is simulated only with a CO_2 concentration larger than 270 ppmv while it was already simulated with a 210 ppmv CO_2 concentration during the Eem. Finally, the ice maxima around 60 and 100 kyr AP follow the insolation minima of $\sim$465 Wm^{-2} occuring at 54 and 98 kyr AP, each of them appearing after a weak maximum. This situation is claimed to be important for past glacial maxima by Berger et al. (1995) and Raymo (1997).

4.2. OUR INTERGLACIAL IN AN INTEGRATION FROM 200 KYR BP TO 130 KYR AP

The experiments (A) described above start at $t = 0$ using the present-day (simulated) ice sheets and bedrocks. A second set of experiments (B, called the non-stop integrations) was performed for the entire time span from 200 kyr BP to 130 kyr AP (Figure 5). In these experiments, the simulated ice sheets and bedrocks for the present day are different from those used in experiments A.

After 30 kyr AP the ice sheets are melted in both experiments A and B using a 290 ppmv CO_2 forcing.

Under the 250 ppmv forcing, important differences between the two sets of simulations persist for the whole time span. In the non-stop integration B, the ice sheets disappear totally from 5 kyr BP and they may barely reappear over the next 130 kyr. Ice maxima are simulated to occur at around 60 kyr AP and 110 kyr AP in both A and B experiments, but they are much larger in A. The present-day

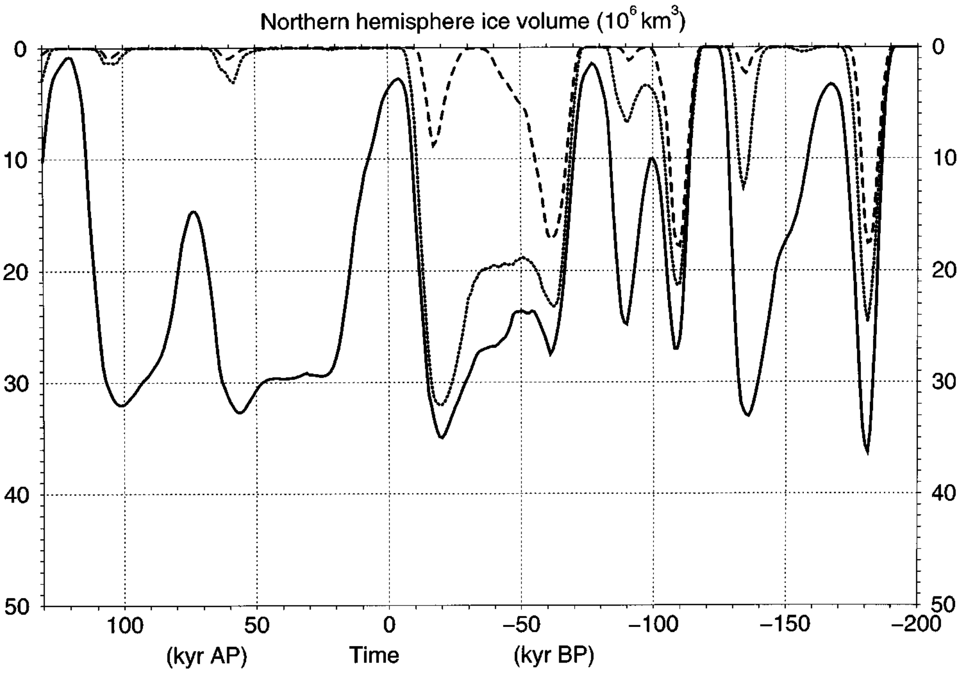

Figure 5. Simulated ice volume of the Northern Hemisphere using the LLN 2-D NH climate model forced by insolation and different constant CO_2 concentrations (210 ppmv in solid line; 250 ppmv in dotted line and 290 ppmv in dashed line) over the last 200 kyr and next 130 kyr. The integrations start with no Greenland ice. These simulations are called non-stop simulations.

size of the Greenland ice sheet and the isostatic rebound below the 3 Northern Hemisphere ice sheets are given in Figure 4 for experiment A and in Figure 6 for the non-stop integration. For North America and Eurasia the differences are not very significant. For Greenland the current existence of 3×10^6 km^3 of ice and of a bedrock depression (Figure 4) contrasts strongly with no ice sheet and a strong isostatic rebound (Figure 6). This difference in the initial conditions explains the differences in the simulated ice volumes given in Figures 3 and 5. In particular, the existence of the present-day Greenland ice sheet explains why the ice volume in the simulation starting with the present-day conditions is much larger.

For the 210 ppmv CO_2 forcing, the ice sheet and bedrock configurations are very similar for the non-stop integration and for the integration A. Consequently, the differences between the 210 ppmv curves of Figures 3 and 5 are small. Nevertheless the entrance into glaciation is steeper in the non-stop integration, the next glacial maximum is reached earlier (at 25 kyr AP) and it is much longer (40 kyr long).

4.3. SENSITIVITY TO THE INITIAL BOUNDARY CONDITIONS

Given the present-day melting of the Northern Hemisphere ice sheets in the non-stop integrations for the 250 and 290 ppmv experiments, it is interesting to compare

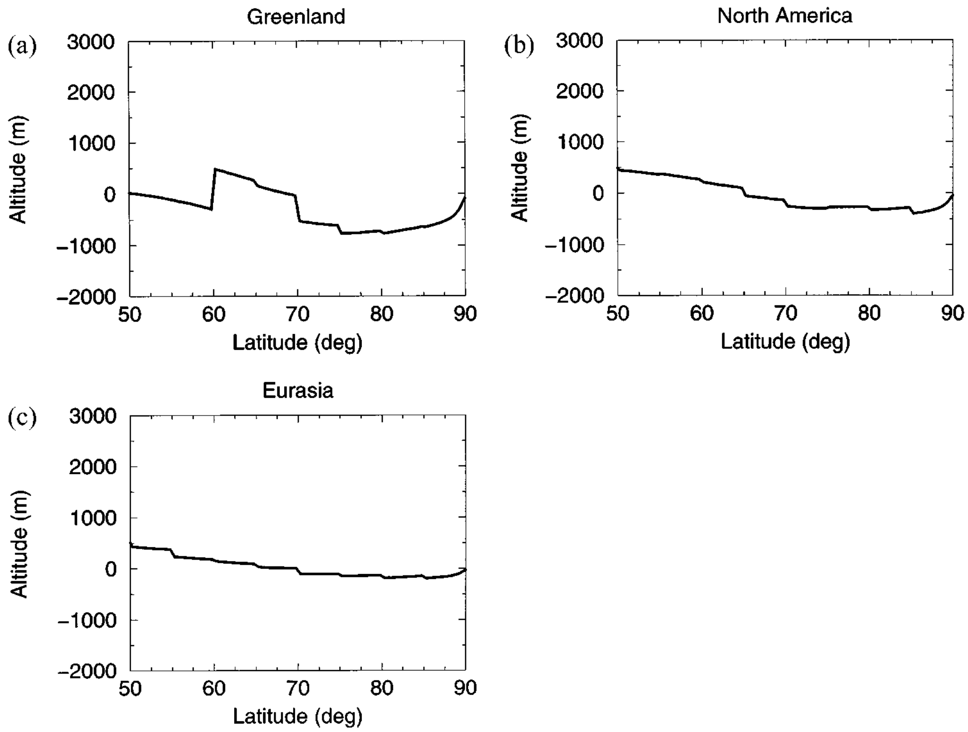

Figure 6. Latitudinal profiles of the present-day bedrock under the Northern Hemisphere ice sheets ((a) Greenland, (b) North America, and (c) Eurasia) in the non-stop simulation with a constant 250 ppmv CO_2 concentration; all Northern Hemisphere ice sheets are melted.

the results of these experiments with those where the integration starts with no ice sheets today, but with the current bedrock depression (Figure 7). This comparison will therefore serve as a sensitivity test of the LLN model to the bedrock initial conditions. The results, displayed in Figure 8 for the three constant CO_2 values, show no significant difference with the non-stop integration of Figure 5 for the 250 and 290 ppmv experiments.

For a CO_2 of 210 ppmv, the difference in the present-day boundary conditions between the two experiments lies in the presence of the Greenland ice sheet (in the non-stop integration) or in its absence (in the no ice sheets – current bedrock depression experiment). This leads to large differences in the simulated Northern Hemisphere ice volumes up to 85 kyr AP. In the 'no ice sheets – current bedrock depression' experiment, the Greenland ice sheet does not reappear significantly before 45 kyr AP. From 50 kyr AP, the Northern Hemisphere ice volume grows rapidly to reach a first maximum just after 60 kyr AP. Although the magnitude of this maximum is 30% smaller than in the non-stop integration (Figure 5), they occur at the same time. This maximum is followed by a slight melting, leading to an amount of ice similar to the experiment of Figure 5 at 70 kyr AP. From

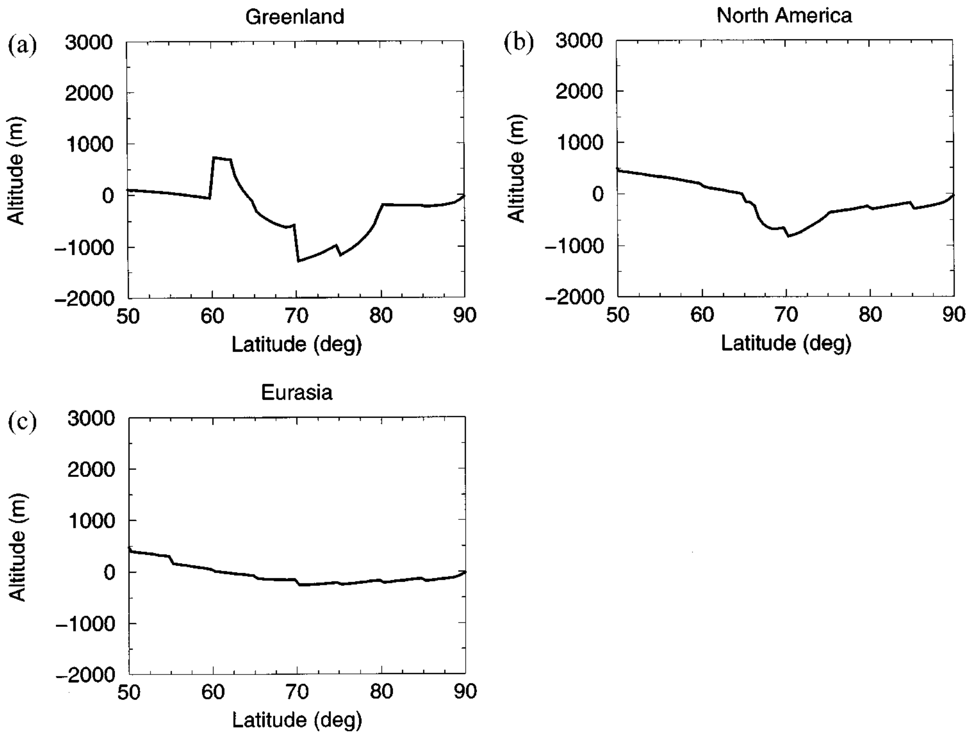

Figure 7. Latitudinal profiles of the present-day bedrock under the Northern Hemisphere ice sheets ((a) Greenland, (b) North America, and (c) Eurasia) used as initial boundary conditions for the simulations shown in Figure 8: all Northern Hemisphere ice sheets are supposed to be melted but current bedrock depression is used.

this date onwards, the ice volume in both experiments becomes very much alike, with a slight difference appearing in the size of the 100 kyr AP maximum and the subsequent melting.

These results indicate that it is primarily the presence of an ice sheet as an initial boundary condition that explains the differences between the experiments of Figures 5 and 7. This sensitivity can be related to the stability of the ice sheets first analysed by Weertman (1961). When accumulation rates fall to low values an ice cap may become unstable and shrink to nothing. Then as the accumulation rate increases again no ice sheet grows until a much greater accumulation value is reached. This reconfirms the important role played by the feedback mechanisms induced by ice.

4.4. THE LAST AND NEXT GLACIAL-INTERGLACIAL CYCLES

Under the high (290 ppmv) CO_2 concentration, no ice-sheet can develop in the future because the insolation variations are too small and the insolation never reaches a value sufficiently low to trigger ice formation. From the simulations of

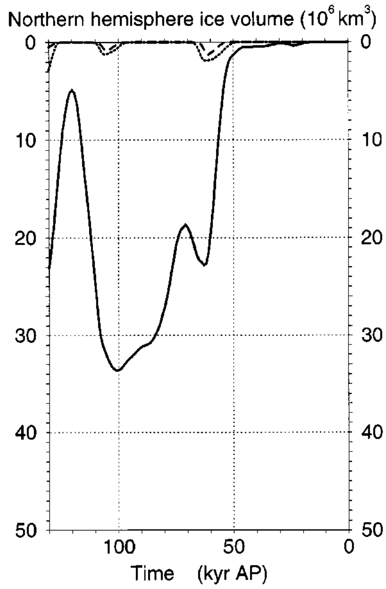

Figure 8. Simulated ice volume of the Northern Hemisphere using the LLN 2-D NH climate model forced by insolation and different constant CO_2 concentrations (210 ppmv in solid line; 250 ppmv in dotted line and 290 ppmv in dashed line) over the next 130 kyr. The integrations start with no present-day Northern Hemisphere ice sheet but with the current bedrock depression.

the past climate, the 65° N June insolation threshold was shown to be lower than $\sim$450 Wm^{-2} for a CO_2 of 290 ppmv . Moreover, the CO_2 threshold concentration leading to an ice age seems to be lower over the next than over the past 130 kyr.

The past climatic variations show a strong 100 kyr periodicity, over which 41, 23 and 19 kyr cycles are superimposed (Figure 5 and Berger et al., 1998a). For the future, two cycles only seem to appear: a long one with a period of about 125 kyr and a shorter one with a period between 45 and 75 kyr. This might result from the weakness of the insolation changes. This, in turn, leads to a large sensitivity to the initial boundary conditions, clearly visible in the simulation of the future climate under the 250 and 210 ppmv CO_2 concentrations (see Figures 3, 5 and 8). On the contrary, experiments starting at 200 or at 125 kyr BP have shown that the model is then not sensitive to the initial boundary conditions (Berger et al., 1998a).

If we accept that the main driving forces of climatic variation on geological time scales are changes in insolation, combined with the chemistry of the atmosphere and the surface boundary layer and feedbacks, it seems logical to accept that the weakness of the insolation changes for the next 100 kyr will give more power to the other factors, in particular to the greenhouse gas concentrations. This conclusion, if confirmed by experiments with more sophisticated models, may be very important in the context of the intensification of the greenhouse effect by human activity.

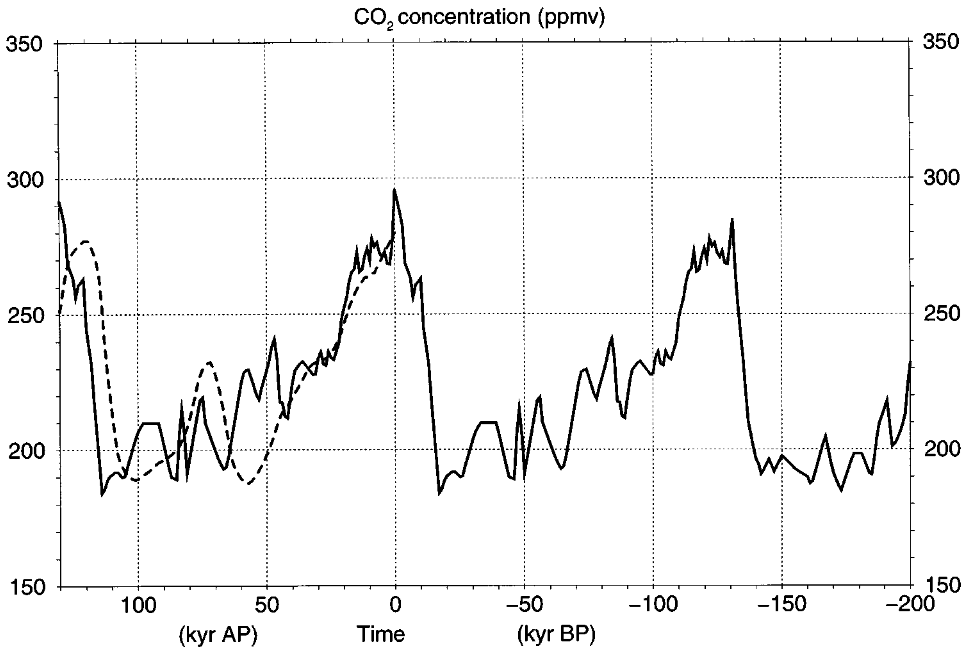

Figure 9. The 'Natural' scenario for the variable CO_2 forcing over the next 130 kyr based upon the CO_2 concentration reconstructed over the last glacial-interglacial cycle by Jouzel et al. (1993) (solid line) compared to a scenario based on a linear regression between the reconstructed CO_2 and the simulated ice volume over the last 200 kyr (dashed line).

5. Future Climate under a Natural Variable CO_2 Scenario

Past CO_2 concentration has undergone large variations. There is no reason why this should not continue to be the case for the future. Since there is no carbon cycle coupled to the LLN 2-D model yet, past CO_2 variations from Jouzel et al. (1993) were used as an approximation to future CO_2 changes over the next 130 kyr. This 'natural' CO_2 scenario is broadly characterised by a slow decrease in the CO_2 atmospheric concentration from 296 ppmv at present (actually the pre-industrial times) to 184 ppmv at 114 kyr AP, followed by a rapid increase up to 291 ppmv at 130 kyr AP (Figure 9). However, the atmospheric CO_2 concentration is, in some complicated ways, related to climate and the insolation over the last glacial-interglacial cycle is very different from the future insolation. This CO_2 scenario can therefore introduce some incoherence between the orbitally-forced climatic changes and the CO_2 forcing.

The major feature of our results (Figure 10) is the unusually long interglacial (lasting until ~50 kyr AP), similar to the situation in the simulations with a constant CO_2 concentration ranging between 230 and 290 ppmv. Starting at 50 kyr AP, there is a global trend in the growth of the ice sheets with a short reversal from 63 to 71 kyr AP, during which 2×10^6 km^3 of ice melts. The next glacial maximum is

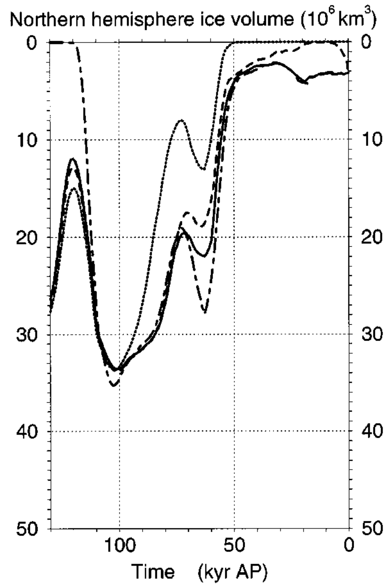

Figure 10. Simulated ice volume of the Northern Hemisphere over next 130 kyr using the LLN 2-D NH climate model forced by insolation and the natural CO_2 scenario shown in Figure 9. Full line: Initial Greenland ice sheet is the present-day one. Dotted line: The integration starts with no ice-sheet in the Northern Hemisphere. Dashed line: CO_2 concentration increases to 750 ppmv over the next 200 yr, then decreases to reach the 1 kyr AP concentration of the Jouzel et al. scenario of Figure 9 and follows this scenario. The results obtained with the linear regression scenario in Figure 9, starting with the present-day Greenland ice sheet, are also displayed (dot-dashed line).

reached at 101 kyr AP with 34×10^6 km^3 of ice. From 110 kyr AP, insolation starts to increase, but the CO_2 concentration remains lower than 200 ppmv until the next insolation maximum is reached at 113 kyr AP. From this time onwards, the CO_2 concentration increases rapidly up to 130 kyr AP, while insolation decreases up to 126 kyr AP. Consequently the simulated continental ice volume reaches a minimum which is still large, amounting to 12.7×10^6 km^3 at 120 kyr BP. This value is much larger than the value simulated with a constant 210 ppmv CO_2 concentration because the CO_2 concentration in the 'natural' scenario remains lower than 210 ppmv and its mean value reaches barely 200 ppmv between 60 and 115 kyr AP.

Scenarios based upon the Shackleton et al. (1992) or Barnola et al. (1987) reconstructions over the last glacial-interglacial cycle were also used for the future 130 kyr. In addition, a linear regression between the Vostok CO_2 and the ice volume (simulated for the last 200 kyr using a 210 ppmv CO_2 concentration) was applied to design another CO_2 scenario for the future (Figure 9). All these scenarios lead to a simulated ice volume, similar to the natural experiment, in the timing as well as in the amount of ice. A long interglacial is followed by the growth of the ice sheets interrupted by a short reversal and followed by a rapid melting. The major difference is the complete melting of the ice sheets at 120 kyr AP with the 'Shackleton scenario' and the 'regression scenario'. This is due to the phase lag between the different scenarios. The maximum of CO_2 occurs roughly at 120 kyr in the 'Shackleton' and the 'regression' scenarios, actually about 10 kyr earlier than in the natural scenario.

The high frequency changes of CO_2 are not reflected in the ice volume simulation because of the long response time of the ice sheets and of the bedrock to such a forcing (see Berger et al. (1998a), their figure 8 in particular). But this is not the case for the air temperature, particularly at some sensitive latitudes where slight changes occur in relation to the insolation changes. For example, at 65–70° N, a decrease in the summer insolation at 15 kyr AP leads to a surface cooling related to a late snow melting: the snow field remains large through the summer and as a consequence, the surface albedo increases. However, the net snow accumulation remains unchanged, the low melting being compensated for by a lower precipitation.

In the latitudinal belt (60–65° N) situated just to the south, the same insolation decrease does not induce any change in the temperature, nor in the snow field. It is only the combination of an even more reduced insolation and a further drop in the CO_2 concentration that will later (after 50 kyr AP) initiate the different feedbacks which are responsible for ice-sheet growth. After 50 kyr AP, in response to these forcings, the summer surface temperature decreases. Simultaneously, the melting of the snow field is delayed, its size extends through the whole summer and the albedo increases resulting in a further cooling. The net accumulation over the ice sheets becomes positive and the ice sheets begin to grow.

The most remarkable feature of this simulation remains the relative steadiness of the modelled Northern Hemisphere climate over the next 50 kyr. Over this time interval, insolation does not reach values low enough to initiate large climatic changes even with a drop of 50 ppmv in the CO_2 concentration. Therefore, other processes than insolation must initiate the different feedbacks, such as the albedo and water vapour feedbacks, which ultimately lead to the buildup of the ice sheets. It is only for very low CO_2 concentration (lower than 200 ppmv), or when insolation and CO_2 combine, or when the Earth is already partly glaciated and the feedbacks are already active, that the Earth enters into an ice age.

The quite arbitrary nature of the CO_2 scenarios and the hypotheses of the model must be kept in mind. However, the robustness of the simulated ice volume over the next 130 kyr should be considered as a reference for the future natural evolution of climate on a geological time scale. Given the plausible impact of human activities on the future climate (Houghton et al., 1996), it is worth testing the sensitivity of natural climate evolution to different scenarios of the intensification of the greenhouse effect over the next centuries.

6. The Possible Human Impact

6.1. NO GREENLAND ICE SHEET TODAY

First we assume that the present-day Greenland ice sheet is absent and that the melting of this ice sheet was rapid enough for the bedrock rebound to have not taken place (Figure 7). The results of the simulations with a constant CO_2 of 210, 250 and 290 ppmv (Figure 8) are compared with the similar simulations starting with the present day ice sheets (Figure 3). Under a CO_2 concentration of 210 ppmv, the entrance into glaciation is delayed and rather more abrupt than when starting with the present-day ice sheet. The model takes between 50 and 60 kyr to override the effects of the initial conditions. Under a CO_2 concentration of 250 ppmv, the Northern Hemisphere remains free of any large ice sheet and the two experiments with different initial conditions remain different over the next 115 kyr (Figures 3 and 8). In 290 ppmv scenario, in the experiment with an initial Greenland ice sheet, the model takes 30 kyr to melt it (Figure 3), but both results are the same afterwards. This intercomparison of results (Figures 3 and 8) may be compared to the one made in Section 4.3 (Figures 5 and 8).

The same sensitivity test on the initial conditions was performed using the so-called ‘natural scenario’ and shows that the ice sheet only reappears after 50 kyr AP (Figure 10: dotted line). This is probably related to the absence of any ice sheet that could otherwise initiate the buildup of large amounts of continental ice in the very peculiar context of a relatively large insolation minimum. It confirms again the importance of ice mechanisms and processes. Up to 100 kyr AP, the simulations with and without an initial ice sheet are parallel, though not identical, with even a phase lag of about 2 kyr between the two simulations around 70 kyr AP. From 100 kyr AP onwards the results are similar.

According to our simulations, the long-term impact of a rapid (instantaneous) melting of the Greenland ice sheet would be a very robust feature of the future climate. The Northern Hemisphere would remain free of ice for at least 50 kyr AP, with further behaviour dependent on the CO_2 concentration. This might reflect a multiple state for the Greenland ice sheet, as emphasised by Crowley and Baum (1995). This complete sudden melting of the Greenland ice sheet might actually result from the global warming related to some very extreme scenarios of future greenhouse gas increases (Loutre, 1995). However, it is a too extreme scenario as it would in reality probably take many millennia, allowing the bedrock to adjust, at least partially. Therefore, more realistic scenarios were designed to test the potential impact of human activities on climate.

6.2. GLOBAL WARMING

A CO_2 scenario (labelled Global Warming, GW) taking into account the impact of man’s activities on the future climate has been used to force the LLN model in addition to insolation. This CO_2 scenario is similar, but not identical, to the IPCC scenario S 750 over the next few centuries (Houghton et al., 1995). It is assumed here that the CO_2 concentration will increase linearly from the pre-industrial value (296 ppmv) to 750 ppmv within 200 yr. It will then decrease slowly to reach the CO_2 concentration of the natural scenario at 1 kyr AP, and follow this scenario up to 130 kyr AP. This GW scenario is much more conservative than most of those discussed by Hasselmann (1997) and Hasselmann et al. (1997).

The procedure to complete this kind of integration is the same as for the natural and other scenarios used up to now, except for the time step.The atmosphere-ocean model is asynchronously coupled to an ice-sheet model. In all palaeoclimatic experiments, the time step of the coupling is 1000 years, but in the GW experiment it is 50 years until 1 kyr AP.

As shown in Figure 10 (dashed line), the ‘global warming’ scenario leads to an almost complete melting of the Greenland ice sheet between roughly 10 and 14 kyr AP. From 15 kyr AP to 50 kyr AP, the ice sheets regrow slowly, and the difference between the natural and the global warming experiments goes from more than 3×10^6 km^3 of ice to less than 1×10^6 km^3. Between 50 and 78 kyr AP, the difference still amounts to a few thousands of km^3 of ice before both simulations start to be similar.

We now compare in more detail the climatic behaviour under the natural CO_2 scenario (N) and the Global Warming scenario (GW). At 1 kyr AP, the simulated Greenland ice sheet is different in the two experiments because of the different scenarios used for CO_2 concentration between 0 and 1 kyr AP. These produce different climates and therefore different ablation/accumulation rates of the ice sheets. Actually, the accumulation and ablation rates resulting from the present-day conditions over Greenland are 31.1 and 10.0 cm/yr respectively. This difference of 21 cm/yr leads to an increase in ice volume which lasts until 1000 yr AP for the natural scenario and only up to 50 yr in the GW scenario. Figure 11 shows clearly the differences in winter and in summer surface temperature between the two experiments. In GW, the winter temperature increases significantly, relative to the present day, in high (10 °C in the 75–80° N zonal belt) and in middle and low latitudes (2.5 °C in the 35–40° N and 5–10° N belts) for the next 200 years. In summer, the warming reaches a little more than 2 °C everywhere over the same time span, except in high polar latitudes. During the same interval, these temperatures are assumed to remain the same as today in the natural scenario as a consequence of the 1 kyr time step used. Even though the insolation and CO_2 forcings are the same at the end of the first one thousand years in both experiments, the air temperature and the other climatic parameters are different because of the response time of the ice-sheet model to the different transient behaviour. The last step of the 1 kyr integration in the GW scenario (from 950 to 1000 yr AP) is characterised by an accumulation-ablation rate of 30.5 and 49.5 cm/yr, that is a net ablation rate of 19 cm/yr instead of the net accumulation rate of the natural scenario. The end product at 1 kyr AP, as far as the Greenland ice sheet is concerned, is a slightly reduced southward extent in GW when compared to N, a smaller ice volume (1.8×10^6

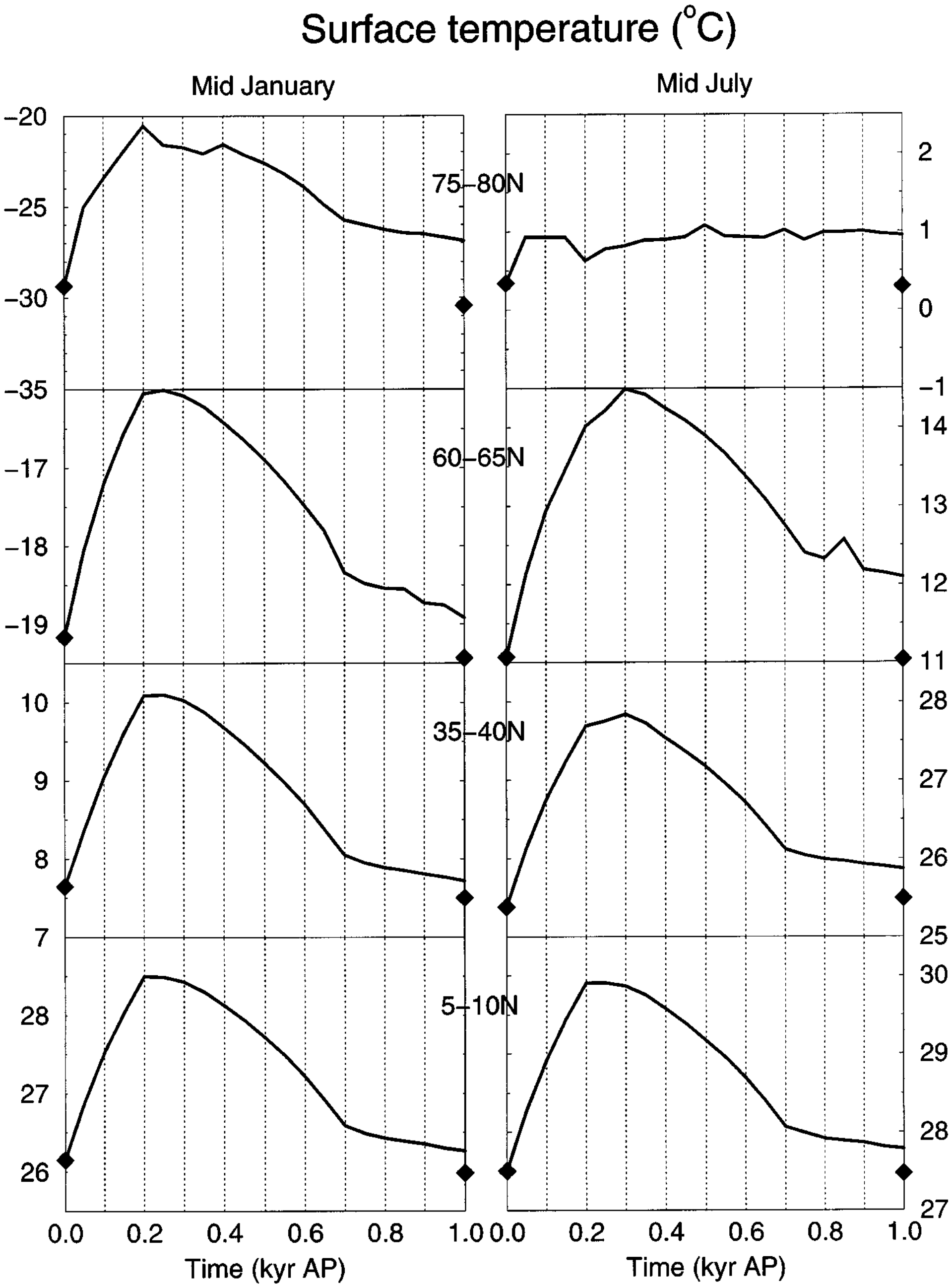

Figure 11. Surface temperature in the latitudinal bands 75°–80° N, 60°–65° N, 35°–40° N, 5°–10° N (from top to bottom), over the next 1000 years, as simulated in the GW experiment (full line) and in the N experiment (filled diamond).

km^3 in GW versus 3.23×10^6 km^3 in N), and consequently a lower ice sheet in GW than in N, with a maximum elevation of the crest of 2401 m and 2873 m respectively.

These significantly different features of the Greenland ice sheet at 1 kyr AP lead to new ablation-accumulation rates calculated by the atmosphere-ocean model at 1 kyr AP. The differences between GW and N lie essentially in the ablation rates. The ice accumulation is similar in both experiments ($\sim$31 cm/yr), but the ablation is larger in GW (48 cm/yr) than in N (9.4 cm/yr) inducing a net ablation of 17.5 cm/yr in GW and a net accumulation of 21.5 cm/yr in N. At the same time, the simulated temperature is higher in GW than in N. The difference in annually averaged values amounts to about 0.5 °C for the entire hemisphere, but it reaches 4 °C in the 65–70 zonal belt and it is of the order of 1 °C in higher latitudes. Large differences arise in the 65–70 band in July (9 °C) in relation to a change of the surface albedo of more than 20% in the zonal and annual mean, a value which contributes significantly to the initiation of an important albedo-temperature feedback.

Different mechanisms play a significant role in strengthening the difference between the GW and N experiments for the next 50 kyr. The difference in the snow field fraction indicates a faster melting of the summer snow in GW than in N, which further reduces the surface albedo. The July mean temperature becomes then larger in GW than in N; the taiga extends in GW, reducing the albedo of the snow-covered vegetated surface (this is the taiga – tundra/albedo feedback). On the other hand, the ablation over the ice sheet is strongly influenced by the downward radiative heat fluxes at its surface, which is larger in GW than in N. The consequence is a temperature difference between the two experiments which lasts from 15 to 40 kyr depending on the latitude and the month. The recovery in temperature actually takes more time in the 65–75 latitude band. Because these latitudes correspond to the southern edge of the ice sheet and because of the permanent snow field there, they are very sensitive to temperature changes which, in turn, initiate the albedo-vegetation – temperature feedback. The annual continental surface albedo in these sensitive latitudes is indeed smaller in GW than in N by more than 25% until 20 kyr AP.

Even when the annual, the January and the July mean temperatures from 60 to 85° N, as well as for the Northern Hemisphere, become similar again in both experiments, differences remain between the simulated ice sheet volumes. At 40 kyr AP, the GW Greenland ice sheet still extends less to the south by 220 km. The simulated ice sheet in GW is lower and thinner than in N at all latitudes along the crest. The differences reach 150 m in altitude and 500 m in thickness at the highest point of the ice sheet. In the south, the ice sheet is melted in GW while it persists in N, inducing a large difference in thickness (around 2000 m). Consequently, the energy balance over the ice sheet remains different for the two experiments, especially in terms of the infrared heat flux. Thus the surface temperature of the ice sheet, and ice accumulation, are also different and these differences last until 50 kyr AP. This indicates clearly that such an anthropogenic warming dominates the

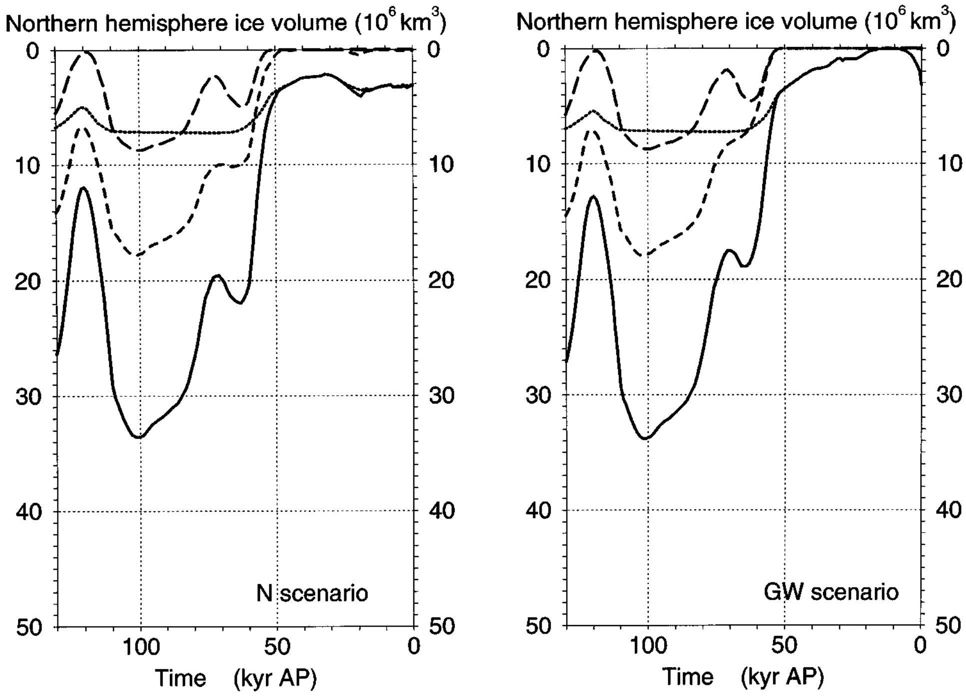

Figure 12. Variation over the next 130 kyr of the ice volume of the Northern Hemisphere (full line), Greenland ice sheet (dotted line), North American ice sheet (dashed line) and Eurasian ice sheet (long-dashed line) as simulated in the GW experiment (right) and in the N experiment (left).

natural astronomical climate variations for at least the next 20 kyr, along the lines discussed in Kim and Crowley (1994).

The ice sheets simulated in GW and N for the next few thousands of years are very different (Figure 12). The GW experiment simulates the almost complete melting of the Greenland ice sheet while this ice sheet is nearly stable in N. Moreover, the Northern Hemisphere ice volumes simulated in the N and the GW experiments remain different until about 80 kyr AP. This difference can be attributed mainly to Greenland from 0 to 50 kyr AP, and to the North American ice sheet from 45 to 75 kyr AP.

7. Is the Melting of the Greenland Ice Sheet Plausible?

Most existing models relate accumulation changes to changes in air temperature, which assumes that warmer air delivers more snow (Alley et al., 1996). Climate change in Greenland could be expected to have immediate effects on the surface mass balance of the ice sheet through melting and runoff as well as through accumulation. With respect to the Greenland ice sheet, according to IPCC (Alley et al., 1996), a warmer climate should increase the melting rate at the margins, and this increase in melting should dominate any increase in accumulation rates in the interior.

More recently (Oerlemans, 1998), a seasonally and regionally differentiated glacier model predicted a melting of the Greenland ice sheet equivalent to 76 mm of sea-level in response to a temperature increase of 2.7 °C. This confirms the net annual surface mass balance decrease on Greenland simulated by the GENESIS model under a doubled atmospheric CO_2 concentration (Thompson and Pollard, 1997). Experiments by Ohmura et al. (1996), Huybrechts et al. (1991) and van de Wal and Oerlemans (1994) all find similar increases in mean Greenland ablation in response to a doubled CO_2. For example, the ECHAM3 GCM simulates a slight decrease in accumulation and a substantial increase in melting over Greenland under doubled carbon dioxide conditions (Ohmura et al., 1996).

Assuming a sudden air temperature increase of 6 °C, Greve's steady state simulations (1997) with a three-dimensional polythermal ice-sheet model show an 87% melting of the Greenland ice sheet over 5 kyr. Fabré et al. (1995) demonstrated that a steady state simulation with 5 °C temperature change yields an ice sheet that almost vanishes with constant present snowfall rates and an ice sheet that is insignificantly different from today's when forced by an exponentially increasing snowfall. Crowley and Baum (1995) provided evidence for a multiple steady state climate for Greenland. Although most CO_2 scenarios do not predict a collapse of the Greenland ice sheet in the future, they suggest that if it did collapse, Greenland may remain in an ice-free state even after the greenhouse effect has dissipated.

However, large and rapid ice sheet melting will lead to huge iceberg discharged. Such Heinrich events are clearly recorded in North Atlantic marine cores during the last glacial period (Bond et al., 1993; Elliot et al., 1998). They have strongly perturbed the ocean circulation and most of them coincide with rapid warm-cold oscillations, the Dansgaard–Oeschger events (Bond and Lotti, 1995; Hewitt et al., 1997; Rasmussen et al., 1997), which are recorded in ice cores, over the continents and in sea-surface temperatures. It was also suggested that iceberg outbursts could significantly reorganise, slow or halt North Atlantic deep water production and thus set the stage for glaciation (Chapman and Shackleton, 1998; Hughes, 1992). Therefore further studies should address the question as to whether the melting of the Greenland ice sheet due to an increase of greenhouse gases could slow down the conveyor belt and induce a negative feedback strong enough to lead to a global cooling or at least to a reduced global warming (Broecker, 1987, 1997; Hughes, 1992; White, 1993; Manabe and Stouffer, 1993; Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999; Schmittner and Stocker, 1999). It is remarkable, however, that in a quadrupling CO_2 simulation which was extended over more than 5000 years, Manabe and Stouffer found that the conveyor belt can recover completely in a couple of thousands of years even after a near standstill appearing about 100 years after the quadrupling (Manabe and Stouffer, 1993; Kerr, 1998). Moreover Manabe and Stouffer (1999b) showed that their model has at least two equilibria, i.e., realistic and active or reverse thermohaline circulation, and that the reverse state is not stable if the diffusion coefficient is large.

8. Conclusions

The main conclusions of this paper are: (i) the unusually long duration of the present interglacial, (ii) the history-dependency of climatic change, (iii) the existence of thresholds for the waxing and waning of the ice sheets, (iv) the significant impact of the human activities during the present and next centuries over more than 50 kyr, and (v) the similarity between stage 11 and our present interglacial underlying the importance of the CO_2 concentration level over these stages.

A series of experiments were performed with the LLN 2-D Northern Hemisphere climate model to assess the future effect of both the astronomical and CO_2 forcings under both natural and anthropogenic influences. The insolation variations over the next 50 kyr are exceptionally small. Similar insolation conditions have occurred only five times over the last 3 million years. In such cases, the amplitude of the simulated ice volume depends strongly on CO_2 concentrations. For a high constant CO_2 concentration of 290 ppmv, the total ice volume is always smaller than now with no continental ice for most of next 130 kyr. With an intermediate value of the CO_2 concentration (250 ppmv), the ice volume remains lower than 15×10^6 km^3, and with a low CO_2 concentration (210 ppmv), it reaches 33×10^6 km^3. These experiments are chracterised by two glacial (or colder) episodes over the next 130 kyr, at about 60 kyr AP and 100 kyr AP. The next interglacial happens at roughly 110 kyr AP, with an interstadial at about 70 kyr AP. These conclusions are confirmed when a natural CO_2 scenario based upon the Vostok record is used. The present interglacial lasts longer than most of the interglacials recorded during the last 10^6 years and is very stable over the next 50 kyr. After 50 kyr AP the ice sheets grow towards the next glacial maximum, which is reached at $\sim$100 kyr AP. The next melting of the continental ice peaks at $\sim$120 kyr AP. Finally, sensitivity experiments show that ice volume simulated under a global warming scenario is strongly dependent on the initial state (present state) of the Greenland ice sheet. This confirms the results obtained from a simple ice-sheet model (Oerlemans and Van der Veen, 1984) showing a long interglacial (50 kyr) followed by a first glacial maximum at $\sim$65 kyr AP, then a slight melting until $\sim$80 kyr AP and the next glacial maximum peaking at $\sim$110 kyr AP.

Our conclusions, in particular the prediction that the present interglacial will have an unusually long duration, are very different from most of the predictions previously made and still confidently referred to at present. All the models reviewed in Berger et al. (1991) concluded that, in the absence of anthropogenic disturbances, the long-term cooling trend which began some 6000 years ago will continue until 25 kyr AP, possibly interrupted by a slight warming at around 15 kyr AP, and will be followed by a major glaciation at 50 kyr AP possibly delayed to 70 kyr AP (Ledley, 1995). All these predictions were based upon statistical relations between insolation and past climate calibrated over the last glacial-interglacial cycle. They therefore do not take into account explicitly any variation of the CO_2 concentration, and contain only information related to the last 200 kyr, in particular the relatively short-lived interglacial of isotopic stage 5e.

From their simulations of the past, Berger et al. (1998b) concluded that, in the case of a cold-glaciated Earth, large CO_2 values are required to counterbalance the surface conditions, while in the case of a warm-ice-free Earth, low CO_2 values are required to enter into glaciation. This history-dependency of climatic change is even stronger when insolation changes are not large enough to drive the climate system. Some insolation thresholds were also identified from simulations of the past. For instance with a 210 ppmv CO_2 concentration the insolation must become larger than 505 Wm^{-2} before ice starts to melt. But it must be lower than 475 Wm^{-2} to induce the buildup of large ice sheets. Since the insolation changes are very weak over the next 40 kyr, the response of the climate system to future insolation will probably depend upon the CO_2 concentration level, and no insolation threshold will be crossed into an ice age. Even after 40 kyr AP the amplitude of the insolation changes remain small. Therefore CO_2 concentration itself must reach a threshold, probably lower than 260 ppmv, before ice sheets start to build.

According to our simulations, man's activities during the 20th to 22nd centuries can significantly impact ice-sheet behavior for more than 50 kyr, depending on the CO_2 scenario and the initial Greenland ice sheet state. In particular, assuming a completely melted Greenland ice sheet as the present-day initial condition, the model takes 70 kyr under low CO_2 forcing to 'forget' this initial condition, i.e., to reproduce the ice volume simulated with an initial Greenland ice sheet of present-day size, while it takes 100 kyr under a variable CO_2 forcing. Under a scenario where the CO_2 concentration reaches 750 ppmv over the next 200 years, and decreases thereafter, the Greenland ice sheet melts almost completely between 10 and 14 kyr AP, a result which is more or less similar to results from more sophisticated models. It re-grows afterwards to reach a volume similar to the volume simulated under the natural CO_2 scenario at 50 kyr AP. This lets us assume that Nature might take as long as 50 kyr to assimilate the impact that Man of the 20th and 21st centuries will have had on the Earth's climate.

This exceptionally great length of the present-day interglacial seems to be seen in the past only once over the last half-a-million years, at isotopic stage 11. Not only the astronomical insolations and the proxy climate indicators are similar to present day, but preliminary results of a simulation, using the CO_2 concentrations from the Vostok ice core reconstruction, leads to a particularly long interglacial around 400 kyr BP. These similarities claim for the importance of the CO_2 concentration level at both isotopic stage 11 and 1, when the amplitude of the insolation variation is remarkably small.

These conclusions are based on the response of the LLN 2-D model to calculated insolation changes and CO_2 scenarios. More experiments will have to be performed, particularly considering scenarios including other greenhouse gases and dust (both tropospheric and volcanic). Moreover, in this model clouds and the hydrological cycle are simplified, the heat transport by the middle and deep oceans should be improved and CO_2 is considered as an external forcing and not as a feedback. Also regional changes, such as in the North Atlantic and over Europe (Rahmstorf, 1997), are not simulated and might depart from the global trend, at least at short time scales. It is expected that all the results presented here will be discussed further using more sophisticated models, in particular 3-D general circulation models and an improved and extended version of the LLN model where both hemispheres, three oceanic basins and employing a better model of the hydrological cycle will be considered.

Acknowledgements

We thank A. Dutrieux for his comments and suggestions. This research was partly funded by the Environment Programme of the Commission of the European Communities under contract CEE-ENV4-CT95-0130 and the Impulse Programme ‘Global Change’ (contract GC/DD/13, Belgian State, Prime Minister’s Office, Federal Office for Scientific, Technical and Cultural Affairs). This research has benefited from computer time provided under contract IT/SC/20 with the Belgian Research Programme on information technology. M. F. Loutre is supported by the Belgian FNRS (Fonds National belge de la Recherche Scientifique). H. Pälike and S. Crowhurst kindly edited the manuscript.

References

Adem, J.: 1996, ‘On the Seasonal Effect of Orbital Variations on the Climates of the Next 4000 Years’, *Annales Geophysicae* **14**, 1198–1206.

Alley, R. B. et al.: 1996, ‘Changes in Sea Level’, in Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *Climate Change 1995. The Science of Climate Change*, Cambridge University Press, Cambridge, U.K., pp. 359–406.

Barnola, J. M., Raynaud, D., Korotkevitch, Y. S., and Lorius, Cl.: 1987, ‘Vostok Ice Core: A 160,000 Year Record of Atmospheric CO_2’, *Nature* **329** (6138), 408–414.

Berger, A.: 1978, ‘Long-Term Variations of Daily Insolation and Quaternary Climatic Changes’, *J. Atmos. Sci.* **35**, 2362–2367.

Berger, A.: 1995, ‘Modelling the Response of the Climate System to Astronomical Forcing’, in Henderson-Sellers, A. (ed.), *Future Climates of the World, A Modelling Perspective*, Vol. 16, World Survey of Climatology (Landsberg, H. E., ed.), Elsevier, Amsterdam, pp. 21–69.

Berger, A. and Loutre, M. F.: 1991, ‘Insolation Values for the Climate of the Last 10 Million Years’, *Quat. Sci. Rev.* **10**, 297–317.

Berger, A. and Loutre, M. F.: 1996, ‘Modelling the Climate Response to Astronomical and CO_2 Forcings’, *C. R. Acad. Sci. Paris* **t.323** (serie IIa), 1–16.

Berger, A. and Loutre, M. F.: 1997, 'Long-Term Variations in Insolation and their Effects on Climate, the LLN Experiment', *Surveys Geophys.* **18**, 147–161.

Berger, A. and Loutre, M. F.: 1998, 'Climate Model in an Astronomical Perspective', in *The Proceedings of the Oslo International Seminar 'Do We Understand Global Climate Change?'*, Norwegian Academy of Technological Sciences, Trondheim, pp. 149–183.

Berger, A., Gallée, H., Fichefet, Th., Marsiat, I., and Tricot, C.: 1990a, 'Testing the Astronomical Theory with a Coupled Climate-Ice Sheet Model', in Labeyrie, L. D. and Jeandel, C. (eds.), *Geochemical Variability in the Oceans, Ice and Sediments*, pp. 125–141.

Berger, A., Fichefet, Th., Gallée, H., Marsiat, I., Tricot, Ch., and van Ypersele, J. P.: 1990b, 'Physical Interactions within a Coupled Climate Model over the Last Glacial-Interglacial Cycle', *Trans. Roy. Soc. Edinburgh: Earth Sciences* **81**, 357–369.

Berger, A., Fichefet, Th., Gallée, H., Marsiat, I., Tricot, Ch., and van Ypersele, J. P.: 1990c, 'Ice Sheets and Sea Level Changes as a Response to Climatic Change at the Astronomical Time Scale', in Paepe, R., Fairbridge, R. W., and Jelgersma, S. (eds.), *Greenhouse Effect, Sea Level and Drought*, Kluwer Academic Publishers, Dordrecht, pp. 85–107.

Berger, A., Gallée, H., and Mélice, J. L.: 1991, 'The Earth's Future Climate at the Astronomical Time Scale', in Goodess, C. and Palutikof, J. (eds.), *Future Climate Change and Radioactive Waste Disposal*, NIREX Safety Series NSS/R257, pp. 148–165.

Berger, A., Fichefet, Th., Gallée, H., Tricot, Ch., and van Ypersele, J. P.: 1992, 'Entering the Glaciation with a 2-D Coupled Climate Model', *Quat. Sci. Rev.* **11**, 481–493.

Berger, A., Tricot, C., Gallée, H., and Loutre, M. F.: 1993a, 'Water Vapour, CO_2 and Insolation over the Last Glacial-Interglacial Cycles', *Phil. Trans. R. Soc. London* **B341**, 253–261.

Berger, A., Gallée, H., and Tricot, Ch.: 1993b, 'Glaciation and Deglaciation Mechanisms in a Coupled 2-D Climate – Ice Sheet Model', *J. Glaciol.* **39** (131), 45–49.

Berger, A., Li, X. S., and Loutre, M. F.: 1995, 'Loess, Deep-Sea Sediment, Ice Sheet Volume and Insolation over the Last 500 ka', in Alfred-Wegener-Stiftung (ed.), *Terra Nostra, Schriften der Alfred-Wegener-Stiftung* 2/95, Boon, p. 161.

Berger, A., Loutre, M. F., and Gallée, H.: 1998a, 'Sensitivity of the LLN Climate Model to the Astronomical and CO_2 Forcing over the Last 200 Kyr', *Clim. Dyn.* **14**, 615–629.

Berger, A., Li, X. S., and Loutre, M. F.: 1998b, 'Modelling Northern Hemisphere Ice Volume over the Last 3 Ma', *Quat. Sci. Rev.* **18**, 1–11.

Bond, G. C. and Lotti. R.: 1995, 'Iceberg Discharge into the North-Atlantic on Millennial Time Scales during the Last Glaciation', *Science* **267** (5200), 1005–1010.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G.: 1993, 'Correlation between Climate Records from North-Atlantic Sediments and Greenland Ice', *Nature* **365** (6442), 143–147.

Broecker, W.: 1987, 'Unpleasant Surprises in the Greenhouse?', *Nature* **328**, 123.

Broecker, W.: 1997, 'Thermohaline Circulation, the Achilles Heel of our Climate System: Will Man-Made CO_2 Upset the Current Balance?', *Science* **278**, 1582–1588.

Broecker, W.: 1998, 'The End of the Present Interglacial: How and When?', *Quat. Sci. Rev.* **17**, 689–694.

Chapman, M. R. and Shackleton, N. J.: 1998, 'Millennial-Scale Fluctuations in North-Atlantic Heat Flux during the Last 150,000 Years', *Earth Planet. Sci. Lett.* **159**, 57–70.

Crowley, T. J.: 1990, 'Are There Any Satisfactory Geologic Analogs for a Future Greenhouse Warming?', *J. Climate* **3**, 1282–1292.

Crowley, T. J. and Baum, S. K.: 1995, 'Is the Greenland Ice-Sheet Bistable?', *Paleoceanography* **10**, 357–363.

Cubash, U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B. D., and Sausen, R.: 1992, 'Time-Dependent Greenhouse Warming Computations with a Coupled Ocean-Atmosphere Model', *Clim. Dyn.* **9**, 55–69.

Elliot, M., Labeyrie, L., Bond, G., Cortijo, E., Turon, J.-L., Tisnerat, N., and Duplessy, J.-C.: 1998, 'Millennial-Scale Iceberg Discharge in the Irminger Basin during the Last Glacial Period: Relationship with the Heinrich Events and Environmental Settings', *Paleoceanography* **13**, 433–446.

Fabré, A., Letréguilly, A., Ritz, C., and Mangeney, A.: 1995, 'Greenland under Changing Climates: Sensitivity Experiments with a Nes Three-Dimensional Ice Sheet Model', *Ann. Glaciol.* **21**, 1–7.

Gallée, H.: 1989, 'Conséquences pour la prochaine glaciation d'une disparition éventuelle de la calotte glaciaire recouvrant le Groenland', Scientific Report 1989/7, Institut d'Astronomie et de Géophysique G. Lemaître, Université catholique de Louvain.

Gallée, H., van Ypersele, J. P., Fichefet, Th., Tricot, C., and Berger, A.: 1991, 'Simulation of the Last Glacial Cycle by a Coupled Sectorially Averaged Climate – Ice-Sheet Model. I. The Climate Model', *J. Geophys. Res.* **96**, 13,139–13,161.

Gallée, H., van Ypersele, J. P., Fichefet, Th., Marsiat, I., Tricot, C., and Berger, A.: 1992, 'Simulation of the Last Glacial Cycle by a Coupled, Sectorially Averaged Climate – Ice-Sheet Model. II. Response to Insolation and CO_2 Variation', *J. Geophys. Res.* **97** (D14), 15,713–15,740.

Goodess, C. M. and Palutikof, J. P. (eds.): 1991, 'Future Climate Change and Radioactive Waste Disposal', in *Proceedings of International Workshop*, Climatic Research Unit, University of East Anglia, Norwich, U.K., p. 261.

Goodess, C. M., Palutikof, J. P., and Davie, T. D.: 1992, *The Nature and Causes of Climatic Change Assessing the Long-Term Future*, Lewis Publishers, Ann Arbor, p. 248.

Greve, R.: 1997, 'Application of a Polythermal Three-Dimensional Ice-Sheet Model to the Greenland Ice-Sheet: Response to a Steady-State and Transient Climate Scenarios', *J. Climate* **10**, 901–918.

Hasselmann, K.: 1997, 'Climate-Change Research after Kyoto', *Nature* **390**, 225–226.

Hasselmann, K., Bengtsson, L., Cubash, U., Hergel, G. C., Rodhe, H., Roecker, E., von Storch, H., Voss, R., and Waskewitz, J.: 1995, 'Detection of Anthropogenic Climate Change Using a Finger Print Method', Max-Planck Institute for Meteorology, Report Nr. 168, Hamburg, p. 20.

Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V., and von Storch, H.: 1997, 'Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM)', *Clim. Change* **37**, 345–386.

Hays, J. D., Imbrie, J., and Shackleton, N. J.: 1976, 'Variations in the Earth's Orbit: Pacemaker of the Ice Ages', *Sciences* **194**, 1121–1132.

Hewitt, A. T., McDonald, D., and Bornhold, B. D.: 1997, 'Ice-Rafted Debris in the North Pacific and Correlation to North Atlantic Climatic Events', *Geophys. Res. Lett.* **24**, 3261–3264.

Houghton, J. T., Merra Filho, L. G., Bruce, J., Hoesung, Lee, Callander, B. A., Haites, E., Harris, N., and Maskell, K. (eds.): 1995, *Climate Change 1994. Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, Cambridge University Press, Cambridge, U.K., p. 339.

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.): 1996, *Climate Change 1995 – The Science of Climate Change*, Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., p. 572.

Howard, W. R.: 1997, 'A Warm Future in the Past', *Nature* **388**, 418–419.

Hughes, T.: 1992, 'Abrupt Climatic Change Related to Unstable Ice Sheet Dynamics. Towards a New Paradigm', *Global Planet. Change* **97**, 203–234.

Huybrechts P., Letréguilly, A., and Reeh, N.: 1991, 'The Greenland Ice Sheet and Greenhouse Warming', *Paleogeogr. Paleoclimatol. Paleoecol.* **89**, 79–92.

Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J.: 1984, 'The Orbital Theory of Pleistocene Climate: Support from a Reised Chronology of the Marine δO^{18} Record', in Berger, A. L., Imbrie, J., Kuka, G., and Saltzman, B. (eds.), *Milankovitch and Climate*, Part I, D. Reidel Publishing, Dordrecht, pp. 269–305.

Johnsen S. J., Dahl-Jensen, D., Dansgaard, W., and Gundestrup, N.: 1995, 'Greenland Palaeotemperatures Derived from GRIP Bore Hole Temperature and Ice Core Isotope Profiles', *Tellus* **47B**, 624–629.

Jouzel, J., Barkov, N. I., Barnola, J. M., Bender, M., Chappellaz, J., Genthon, C., Kotlyakov, V. M., Lorius, Cl., Petit, J. R., Raynaud, D., Raisbeck, G., Ritz, C., Sowers, T., Stievenard, M., Yiou, F., and Yiou, P.: 1993, 'Vostok Ice Cores: Extending the Climatic Records over the Penultimate Glacial Period', *Nature* **364** (6436), 407–412.

Kerr, R. A.: 1998, 'Warming's Unpleasant Surprise: Shivering in the Greenhouse?', *Sciences* **181**, 156–158.

Kim, K.-Y. and Crowley, T. J.: 1994, 'Modeling the Climate Effect of Unrestricted Greenhouse Emissions over the Next 10,000 Years', *Geophys. Res. Lett.* **21**, 681–684.

Kukla, G. J., Matthews, R. K., and Mitchell, M. J.: 1972, 'Present Interglacial: How and When Will it End?', *Quatern. Res.* **2**, 261–269.

Kukla, G., MacManus, J. F., Rousseau, D. D., and Chuine, I.: 1997, 'How Long and How Stable Was the Last Interglacial?', *Quat. Sci. Rev.* **16**, 605–612.

Ledley, T. S.: 1995, 'Summer Solstice Solar-Radiation, the 100 Kyr Ice-Age Cycle, and the Next Ice-Age', *Geophys. Res. Lett.* **22**, 2745–2748.

Li, X. S., Berger, A., Loutre, M. F., Maslin, M. A., Haug, G. H., and Tiedemann, R.: 1998a, 'Simulating Late Pliocene Northern Hemisphere Climate with the LLN 2-D Model', *Geophys. Res. Lett.* **25**, 915–918.

Li, X. S., Berger, A., and Loutre, M. F.: 1998b, 'CO_2 and Northern Hemisphere Ice Volume Variations over the Middle and Late Quaternary', *Clim. Dyn.* **14**, 537–544.

Lorius, C., Jouzel, J., Raynaud, D., Hansen, J., and Le Treut, H.: 1990, 'The Ice-Core Record: Climate Sensitivity and Future Greenhouse Warming', *Nature* **347**, 139–145.

Lorius, C., Jouzel, J., and Raynaud, D.: 1993, 'Glacials-Interglacials in Vostok: Climate and Greenhouse Gases', *Global Planet. Change* **7**, 131–143.

Loutre, M. F.: 1995, 'Greenland Ice Sheet over the Next 5000 Years', *Geophys. Res. Lett.* **22**, 783–786.

Manabe, S. and Stouffer, R. J.: 1993, 'Century-Scale Effects of Increased Atmospheric CO_2 on the Ocean-Atmosphere System', *Nature* **364**, 215–218.

Manabe, S. and Stouffer, R. J.: 1994, 'Multiple-Century Response of a Coupled Ocean-Atmosphere Model to an Increase of Atmospheric Carbon Dioxide', *J. Climate* **7**, 5–23.

Manabe, S. and Stouffer, R. J.: 1999a, 'The Rôle of Thermohaline Circulation in Climate', *Tellus* **51A–B**, 91–109.

Manabe, S. and Stouffer, R. J.: 1999b, 'Are Two Modes of Thermohaline Circulation Stable?', *Tellus* **51A**, 400–411.

Mikolajewicz, U. and Maier-Reimer, E.: 1994, 'Mixed Boundary Conditions in Ocean General Circulation Models and their Influence on the Stability of the Model's Conveyor Belt', *J. Geophys. Res.* **99**, 22633–22644.

Mitchell, J. M., Jr.: 1972, 'The Natural Breakdown of the Present Interglacial and its Possible Intervention by Human Activities', *Quatern. Res.* **2**, 436–445.

Mitchell, J. F. B.: 1990, 'Greenhouse Warming: Is the Mid-Holocene a Good Analogue?', *J. Climate* **3**, 1177–1192.

Mitchell, J. F. B., Johns, T. C., Gregory, J. M., and Tett, S. F. B.: 1995, 'Climate Response Ton Increasing Levels of Greenhouse Gases and Sulphate Aerosols', *Nature* **376** (6540), 50–504.

Oerlemans, J.: 1998, 'Simulated Future Sea-Level Rise Due To Glacier Melt Base on Regionally and Seasonally Resolved Temperature Changes', *Nature* **391** (6666), 474–476.

Oerlemans, J. and Van der Veen, C. J.: 1984, *Ice Sheets and Climate*, Reidel Publishing, Dordrecht, p. 217.

Ohmura, A., Wild, M., and Bengtsson, L.: 1996, 'A Possible Change in Mass Balance of Greenland and Antarctic Ice Sheets in the Coming Century', *J. Climate* **9**, 2124–2135.

Oppo, D. W., McManus, J. F., and Cullen, J. L.: 1998, 'Abrupt Climate Events 500,000 to 340,000 Years Ago: Evidence from Subpolar North Atlantic Sediments', *Nature* **279**, 1335–1338.

Rahmstorf, S.: 1997, 'Risk of Sea-Change in the Atlantic', *Nature* **388** (6645), 825–826.

Rahmstorf, S. and Ganopolski, A.: 1999, 'Long-Term Global Warming Scenarios Computed with an Efficient Coupled Climate Model', *Clim. Change* **43**, 353–367.

Rasmussen, T. L., Van Weering, T. C. E., and Labeyrie, L.: 1997, 'Climatic Instability, Ice Sheets and Ocean Dynamics at High Northern Latitudes during the Last Glacial Period (58-10 ka BP)', *Quat. Sci. Rev.* **16**, 71–80.

Raymo, M. E.: 1997, 'The Timing of Major Climate Terminations', *Paleoceanography* **12**, 577–585.

Saltzman, B. and Verbitsky, M.: 1994, 'CO_2 and Glacial Cycles', *Nature* **367**, 419.

Saltzman, B., Maasch, K. A., and Verbitsky, M. Y.: 1993, 'Possible Effects of Anthropogenically-Increased CO_2 on the Dynamics of Climate: Implications for Ice Age Cycles', *Geophys. Res. Lett.* **20**, 1051–1054.

Schmittner, A. and Stocker, T. F.: 1999, 'The Stability of the Thermohaline Circulation in Global Warming Experiments', *J. Climate* **12**, 1117–1133.

Shackleton, N. J., Le, J., Mix, A., and Hall, M. A.: 1992, 'Carbon Isotope Records from Pacific Surface Waters and Atmospheric Carbon Dioxide', *Quat. Sci. Rev.* **11**, 387–400.

Stocker, T. F. and Wright: 1991, 'Rapid Transitions of the Ocean's Deep Circulation Induced by Changes in Surface Water Fluxes', *Nature* **351**, 729–732.

Stocker, T. F. and Schmittner, A.: 1997, 'Influence of CO_2 Emission Rates on the Stability of the Thermohaline Circulation', *Nature* **388**, 862–865.

Thompson, S. L. and Pollard, D.: 1997, 'Greenland and Antarctic Mass Balances for Present and Doubled Atmospheric CO_2 from the GENESIS Version-2 Global Climate Model', *J. Climate* **10**, 871–900.

Van de Wal, R. S. W. and Oerlemans, J.: 1994, 'An Energy Balance Model for the Greenland Ice Sheet', *Global Planet. Change* **9**, 115–131.

Weertman, J.: 1961, 'Stability of Ice-Age Ice Sheets', *J. Geophys. Res.* **66**, 3783–3792.

White, J. W. C.: 1993, 'Don't Touch that Dial', *Nature* **364**, 186.

Winograd, I. J., Landwehr, J. M., Ludwig, K. R., Coplen, T. B., and Riggs, A. C.: 1997, 'Duration and Structure of the Past Four Interglacials', *Quatern. Res.* **48**, 141–154.

(Received 30 July 1998; in revised form 30 July 1999)