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MODELING THE RESPONSE OF THE CLIMATE SYSTEM TO THE ASTRONOMICAL FORCING DURING THE QUATERNARY

Modélisation de la réponse du système climatique au forcing astronomique pendant le Quaternaire

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RESUME

Le modèle climatique LLN 2-D a été utilisé pour restituer les variations à long terme des glaciations quaternaires. Les analyses qui ont été menées, prennent en considération les variations de l'insolation dues à des causes astronomiques ainsi que la décroissance linéaire de la concentration en CO2 de 320 à 200 ppmv entre le Pliocène supérieur et le Dernier Maximum Glaciaire. En se fondant sur de telles conditions, le modèle a reproduit l'intensification de la glaciation vers 2,75 Ma BP, l'intervention de cycle de 41 ka entre le Pliocène et le Pléistocène, l'émergence du cycle de 100 ka autour de 900 ka BP et les cycles glaciaire-interglaciaire au cours des dernières 600 ka.

L'hypothèse était avancée que durant le Pliocène tardif - dans un monde dépourvu de glaciers - des calottes glaciaires ne pouvaient se développer que pendant des périodes d'insolation estivale réduite. Ceci demande une excentricité élevée, assortie d'une précession et d'une obliquité adéquate, amenant une période de 41 ka entre 3 et 1 Ma BP. Au contraire, dans un monde non dépourvu de glaces, les calottes glaciaires persisteraient si toutefois l'insolation n'est pas trop élevée aux latitudes polaires, ce qui exigerait également une excentricité élevée, mais aboutissant cette fois à un interglaciaire et finalement à une période de 100 ka pendant le dernier Ma. Une évaluation de la concentration en CO2 grâce à une régression utlisant le programme SPECMAP a montré que les stades isotopiques 11 et 1 demande une haute teneur en CO2 pour produire un interglaciaire. Les variations de l'insolation au cours de ces deux stades et les résultats du modèle indique que le stade 11 est un meilleur indicateur que l'Eemien pour l'évolution future du climat. Bien que les seules variations de l'insolation agissent comme un pacemaker en ce qui concerne les cycles glaciaire-interglaciaire, les variations de la teneur en CO2 contribuent à mieux reproduire les variations du climat du passé, plus particulièrement celles de la température de l'air et de l'extension, vers le Sud des calottes glaciaires. La simulation du climat des prochaines 130 ka a montré que le présent interglaciaire sera particulièrement long (50 ka). Cette conclusion est encore renforcée si l'on prend en considération l'intensification possible de l'effet de serre dû aux activités humaines pendant les prochains siècles.

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ABSTRACT

The LLN 2-D climate model has been used to reconstruct the long-term climatic variations over the Quaternary Ice Age. Sensitivity analyses to the astronomically-driven insolation changes and to the CO2 atmospheric concentration have been performed. In particular, an atmospheric CO2 concentration decreasing linearly from 320 ppmv at 3 Myr BP (Late Pliocene) to 200 ppmv at the Last Glacial Maximum was used to force the model in addition to the insolation. Under such condition, the model simulates the intensification of glaciation around 2.75 Myr BP, the late Pliocene-early Pleistocene 41-kyr cycle, the emergence of the 100-kyr cycle around 900 kyr BP, and the glacial-interglacial cycles of the last 600 kyr. The hypothesis was put forward that during the Late Pliocene (in an ice-free-warm world) ice sheets can only develop during times of sufficiently low summer insolation. This occurs during large eccentricity times when climatic precession and obliquity combine to obtain such low values, leading to the 41-kyr period between 3 and 1 Myr BP. On the contrary in a glacial world, ice sheets persist most of the time except when insolation is very high in polar latitudes, requiring large eccentricity again, but leading this time to interglacial and finally to the 100-kyr period of the last 1 Myr. Using a reconstructed CO2 concentration over the last 600 kyr from a regression based upon SPECMAP, it has been shown that stage 11 and stage 1 request a high CO2 to reach the interglacial level. The insolation profile at both stages and modeling results tend to show that stage 11 might be a better analogue for our future climate than the Eem. Although the insolation changes alone act as a pacemaker for the glacial-interglacial cycles, CO2 changes help to better reproduce past climatic changes and, in particular, the air temperature and the southern extend of the ice sheets. Using the calculated insolation and a few scenarios for CO2, the climate of the next 130 kyr has been simulated. It shows that an interglacial will most probably last particularly long (50 kyr). This conclusion is reinforced if we take into account the possible intensification of the greenhouse effect which might result from man's activities over the next centuries.

INTRODUCTION TO THE MILANKOVITCH THEORY

The current Ice Age, which the Earth entered 2 to 3 million years ago, is called the Quaternary Ice Age. It is characterized by multiple switches of the global climate between glacials (with extensive ice sheets) and interglacials (with a climate similar to or warmer than today by a few degrees Celsius). Over the last million years, the waxing and waning of ice sheets occurred in a more or less regular way. Reconstructions of long-term climatic variations, like the ice volume and sea level, show a sawtooth shape with a 100-kyr quasi-cycle over which shorter quasi-cycles of roughly 41 and 21 kyr are superimposed (BERGER, 1988). The last cycle goes from the Eemian interglacial times, centered roughly 125 kyr BP, to the present-day Holocene interglacial which peaked 6 kyr BP. It includes the Last Glacial maximum (LGM) which occurred 20 kyr BP. In the Northern Hemisphere, the LGM would differed strikingly from the present in the huge land-based ice sheets, reaching approximately 2 to 3 km in thickness and amounting to about 40 x 106 km3 of ice. Sea level was lower by roughly 110 m and the global average surface air temperature was ±5°C below present. CO2 levels were less than two thirds their present value and aerosol loading may have been higher than present.

But the 100-kyr cycle, so dominant a feature of the late Pleistocene record, does not exhibit a constant amplitude over the past 3 million years. Many spectral analyses from PESTIAUX & BERGER, (1984) to BOLTON *et al.* (1998) showed that this periodicity disappears before 1 Myr BP roughly, the climatic variability being dominated by the 41-kyr cycle during the Late Pliocene and early Pleistocene.

These kinds of broad climatic features are those explained by the astronomical theory of paleoclimates. Proponents of this theory claim that the changes in the Earth's orbital and rotational parameters have been sufflciently large as to induce significant changes in the seasonal and latitudinal distributions of irradiation received from the Sun and so, to force glacials and interglacials to recur in the manner deduced from geological records. In this process, feedbacks due to changes in the albedo, the water vapour and other greenhouse gases play a fundamental role.

The incoming solar radiation received over the Earth has an annual periodic variation due to the Earth's elliptic translation motion around the Sun. But in addition, the seasonal and latitudinal distributions of this solar radiation have a long-period variation due to the so-called long-term variations in the astronomical elements (BERGER, 1996a, 1996b). These are the eccentricity e, a measure of the shape of the Earth's orbit around the Sun, the obliquity ε, the tilt of the equator with respect to the plane of the Earth's orbit, and the climatic precession, $e\sin\varpi$, a measure of the Earth-Sun distance at the summer solstice.

According to theoretical calculations (BERGER, 1978), the eccentricity of the Earth's orbit varies between near circularity ($e = 0$) and slight ellipticity ($e=0.07$) at a period which mean is about 100 kyr. The most important terms in the series expansion occur however at 404, 95, 124, 99, 131 and 2,380 kyr (in decreasing order of amplitude). The tilt of the Earth's axis varies between about 22° and 25° at a period of nearly 41 kyr. As far as precession is concerned, the equinoxes and solstices shift slowly around the Earth's orbit relative to the perihelion, with a mean period of 21 kyr (it is measured by the longitude, ϖ, of the moving perihelion). This period results actually from the existence of two periods which are close to each other: 23 and 19 kyr. In the insolation formulas used to study past and future astronomical forcing of climate, the amplitude of $\sin\varpi$ is modulated by eccentricity in the term $e\sin\varpi$.

The combined influence of changes in e, ε, and $e\sin\varpi$ produces a complex pattern of insolation variations. A detailed analysis of the changes in daily solar radiation (BERGER *et al.*, 1993a) shows that it is principally affected by variations in precession, although the obliquity plays an important role for high latitudes, mainly in the winter hemisphere.

The orbital hypothesis of climatic change was first quantitatively formulated by the astronomer Milutin Milankovitch in the 1920s. He argued (MILANKOVITCH, 1941) that insolation changes in the high northern latitudes during the summer season were critical to the formation of continental ice sheets. During periods when insolation in the summer was reduced, the snow of the previous winter would tend to be preserved, a tendency that would be enhanced by the high albedo of the snow and ice areas. Eventually, the effect of this positive feedback would lead to the formation of persistent ice sheets.

A simple linear version of the Milankovitch model predict therefore that the proxy record of climate variations would contain the frequencies of the astronomical parameters that are responsible for changing the seasonal and latitudinal distributions of incoming solar radiation. It happens that investigations since the late 1970s have indeed demonstrated that the 19-, 23-, and 41- kyr periodocities actually occur in long records of the Quaternary climate (HAYS *et al.*,1976; IMBRIE *et al.*,1992). However, the same investigation identified also the largest climatic cycle as being 100 kyr. As this eccentricity cycle is very weak in the insolation (BERGER *et al.*, 1993a), it cannot be related to the orbital forcing by any simple linear mechanism (IMBRIE *et al.*, 1993).

Over the last 25 years, a number of modelling efforts have attempted to explain the relationship between astronomical forcing and climatic change (BERGER, 1995). Most of these modelling studies have focused on the origin of the 100-kyr cycle, because it is recognized that the amount of insolation perturbation at the 100-kyr period is not enough to cause a climatic change of ice-age amplitude by itself. Although these models are based on parameters which are considered to be physically plausible, they are all simpliflied. What these models do confirm is that the response to orbital forcing is non-linear and that it involves internal processes and feedback mechanisms. Whether the external orbital forcing drives the internal processes, phase-locks the oscillations of an internally driven system, or acts as a pacemaker for the free oscillations of an internally driven system remains, however, an open question.

As a consequence, the discussion of how the dimate system responds to orbital forcing calls for the construction of a physically realistic model of the time-dependent behaviour of the coupled climate system, including the atmosphere, the oceans, the cryosphere, the lithosphere and the biosphere. At that time-scale, plate tectonics, mantle convection, mountain building and sun evolution are kept constant.

LLN 2-D MODEL

It was suggested earlier (BERGER, 1979) that the time-evolution of the latitudinal distribution of the seasonal pattern of insolation is the key factor driving the behaviour of the climate system while the complex interactions between its different parts amplify this orbital perturbation. That dynamical behaviour of the seasonal cycle suggests that time-dependent coupled climate models might be able to test whether or not the astronomical forcing can drive the long-term climatic variations. Such time-dependent climate models must therefore be forced only by the astronomical variations of insolation for each latitude and day, the so-called boundary conditions used in equilibrium atmospheric general circulation model experiments (ice-sheet size and area, sea-surface temperature, albedo, etc.) being all generated by the climate model itself.

Such a climate model has been constructed in Louvain-la-Neuve and forced by the astronomical variations of insolation for each latitude and day and by different scenarios of CO2 concentration. The purpose of this paper is to summarize the results of recent experiments made with this model. We will see, in particular, that under the forcing of insolation and of an atmospheric CO2 concentration decreasing linearly from 320 ppmv at 3 Myr BP to 200 ppmv at the Last Glacial maximum, the model simulates the entrance into glaciation around 2.75 Myr BP (LI *et al.*, 1998b), the late Pliocene-early Pleistocene 41-kyr cycle, the emergence of the 100-kyr cycle around 900 kyr BP (BERGER *et al.*, 1998a) and the glacial-interglacial cycles of the last 600 kyr (LI *et al.*, 1998a). Using a reconstruction, where CO2 varies with the climatic cycles, improves further the agreement between model results and the oxygen isotope time series, especially as far as the amplitude of the signal is concerned.

The LLN climate model links the Northern Hemisphere atmosphere, ocean mixed layer, sea-ice, ice sheets and continents (GALLEE *et al.*, 1991). It is a latitude-altitude model. In each latitudinal belt, the surface is divided into at most seven oceanic or continental surface types, each of which interacting separately with the subsurface and the atmosphere. The oceanic surfaces are ice-free ocean and sea-ice cover, while the continental surfaces are the snow-covered and snow-free lands and the Northern Hemisphere ice sheets.

The atmospheric dynamics is simulated by a two-level quasi-geostrophic model written in pressure coordinates and zonally averaged. Although the model domain is limited to the Northern Hemisphere a cross-equatorial heat flux is allowed. Precipitations over the ice sheets are corrected to take into account the surface slope, the elevation and the continentality of these ice sheets. For the calculation of the radiative fluxes, the vertical temperature profile in the troposphere is determined from the static stability parameter and the pressure. The vertical variation of specific humidity is deduced from the zonally averaged surface temperature and relative humidity. Annual mean and monthly distribution of the zonal cloudiness are prescribed. The calculation of the solar radiation takes into account absorption by H2O, CO2 and O3, Rayleigh scattering, absorption and scattering by cloud and aerosol layers, and reflection by the surface. The longwave radiation scheme follows a formulation used in GCM's. 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 surface energy balance and snow and sea-ice budgets.

The vertical profile of the upper ocean temperature is computed by a mixed-layer model. The oceanic transport and its influence on the sea-surface temperature are simulated through a diffusive parameterization of the meridional convergence of heat. Sea ice is represented by a thermodynamic model including leads and a parameterization of lateral accretion.

A special attention is paid to the albedo of snow, of vegetation in the tundra/taiga regions, of sea water and of sea ice. More details on the model are given in GALLEE *et al.* (1991) and also in BERGER *et al.* (1990) for the ice sheet-lithosphere model, in BERGER *et al.* (1989) for the upper ocean and in BERGER *et al.* (1994) for the radiative convective scheme.

Simulation of the present climate shows that the model is able to reproduce the main characteristics of the atmospheric general circulation and the seasonal cycles of the oceanic mixed layer, of the sea ice, and of the snow cover (GALLEE *et al.*, 1991).

This atmosphere-ocean model is asynchronously coupled to a model of the three main Northern Hemisphere ice sheets and their underlying bedrock in order to simulate the long-term climatic changes. The coupled climate model is then forced by the astronomically-derived insolation and by the atmospheric CO2 concentration, because the model does not contain any carbon cycle yet. Different experiments made with this model over the last glacial-interglacial cycles have shown that it is able to reproduce the broad features of the low frequency part of past climatic variations (GALLEE *et al.*, 1992; LI *et al.*, 1998a).

Besides the forcings, modeling results indicate that some particular processes and feedbacks play a very important role. These are the water-vapor feedback (BERGER *et al.*, 1993b), the albedo-temperature feedback, in particular related to the snow covered taiga versus tundra in high polar latitudes, the altitude and continental effects on the snow precipitations over the ice sheets, the snow-ageing process and the isostatic rebound (BERGER *et al.*, 1992, 1993c). It also shows clearly the difference in phases between the astronomical forcing and the response of the ice sheets, of the continental and oceanic surfaces, and of the atmosphere.

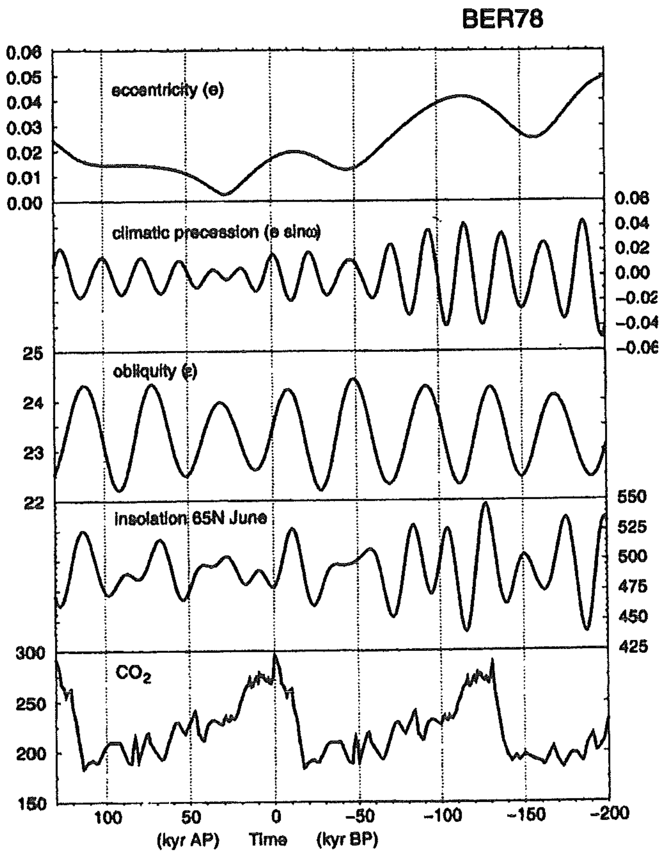

Fig. 1.: Long term variations of eccentricity, precession, obliquity, summer solstice insolation at 65°N (BERGER, 1978) and atmospheric CO 2 concentration (JOUZEL et al., 1993 for the past) from 200 kyr BP to 130 kyr AP.

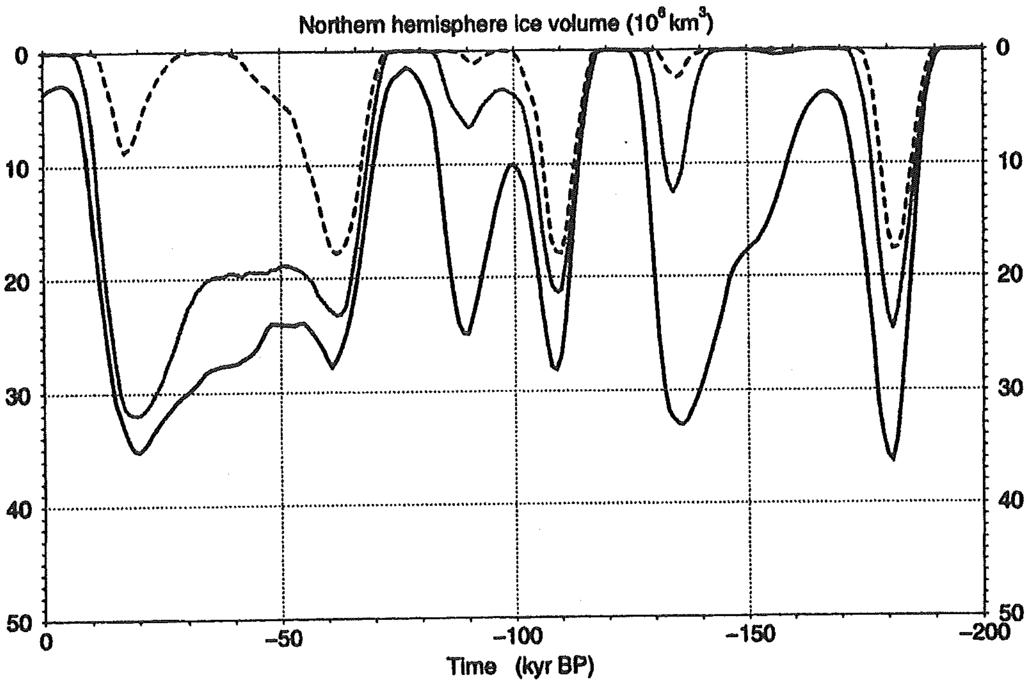

Fig. 2.: Simulated ice volume of the Northern Hemisphere using the LLN 2-D NB climate model forced by insolation and a constant CO 2 concentration over the last 200 kyr (210 ppmv in full lime, 250 ppmv in dotted lime and 290 ppmv in dashedline).

SENSITIVITY OF THE LLN 2-D MODEL TO CO2

Since the publication of HAYS *et al.* (1976), the major question remains whether or not the astronomically-induced changes in solar radiation received on the Earth are able to generate the climatic changes reconstructed independently by geologists.

To test this astronomical hypothesis, all external forcings (including CO2), except the insolation changes (Fig. 1), have to be kept constant. Experiments were therefore performed (BERGER *et al.*, 1998b) with three selected constant CO2 concentrations - low (210 ppmv), high (290 ppmv) and medium (250 ppmv) - which corresponds to an average concentration for, respectively, glacial, interglacial and intermediate times. Most of the time, during the last 200 kyr at least, CO2 is varying around 225 ppmv (between 210 and 250 ppmv), higher values being reached only during the interglacials (the pre-industrial value, representative of our Holocene interglacial is ± 280 ppmv, but the present-day level is already 360 ppmv (HOUGHTON *et al.*, 1996), more than 20 % above the interglacial levels and about twice as much as during the glacial maximum).

The conclusions that we can draw from such experiments (Fig.2) are the following:

First, a frequent melting of the ice sheets occur under a high CO2 concentration (290 ppmv and even 250 ppmv).

Second, only the CO2 concentration of 210 ppmv provides a simulation which might be compared to the geological reconstructions, the two other experiments leading to an amplitude of the ice volume variations which is far less than in geological reconstructions. When CO2 is kept at its glacial value (210 ppmv), the amplitude of the ice volume change is about 35 x 106 km3, but the amount of ice remains always lower than 20 x 106 km3 when the CO2 concentration is 290 ppmv. Actually, it appears that the CO2 level of 210 ppmv is low enough to allow the albedo-temperature and water vapor-temperature feedbacks to start playing their fundamental role in amplifying the direct climatic impact initiated by the orbitally-induced insolation changes. The analysis of the spectra of the Northern Hemisphere ice volume simulated under a 210, 250 and 290 ppmv forcing confirms that the coherency with the SPECMAP data is significant (at the 5 % level) in the precession, obliquity and eccentricity bands only for 210 ppmv (Fig. 3). However, a major deficiency remains in the results of the 210 ppmv experiment: the Northern Hemisphere ice sheets melt too often during some interglacials while there is evidence that the Greenland ice sheet survived over the last 2 to 3 glacial-interglacial cycles at least (DANSGAARD *et al.*, 1993). It was shown (GALLEE *et al.*, 1993) that this shortcoming does not prevent the ice sheets to grow again leading to a 100 kyr quasi-cyclicity similar to the one seen in the geological data.

Third, the response of the climate system is far from being linear in CO2. Relatively large volumes of ice are created for the three CO2 levels at 181, 109 and 61 kyr BP, with each time the 250 ppmv curve being situated half-way between the 210 and 290 ppmv ones (at these three dates the differences between the results of these 2 extreme CO2-concentration experiments are respectively 20 and two times 10 x 106 km3). This is not the case for the other ice maxima. At 136 and 90 kyr BP, large ice sheets appear only for 210 ppmv, the differences between the 210 and 290 ppmv cases amounting to respectively 30 and 25 x 106 km3. At these two dates, the 250 ppmv simulation is definitely doser to the 290 ppmv one. In contrast, at 20 kyr BP, the difference between the low and the high CO2 experiments amounts also to more than 25 x 106 km3, but the 250 ppmv simulated ice maximum is here very closely tied to the 210 ppmv one.

To summarize, if we compare the response of the model to the astronomical forcing in all three CO2 experiments we can conclude that:

1) The behaviour of the climate system which leads to the ice maxima of 181, 109 and 61 kyr BP is similar in the three cases. Insolation reaches its deepest minimum 7 to 11 kyr before (440 Wm-2 at 188 kyr BP, 440 Wm-2 at 116 kyr BP and 453 Wm-2 at 72 kyr BP) and ice sheets form under the three CO2 concentrations. At these times eccentricity is large, summer solstice occurs close to aphelion and obliquity is low.

2) At the ice maxima of 136, 90 and 20 kyr BP, the two extreme CO2 levels lead to totally different simulated ice volumes. This reveals a very high sensitivity of the LLN climate model to CO2 at these times which correspond to secondary minima in the insolation curve. Let us recall that the 250 ppmv curve is associated to the 210 ppmv curve at the Last Glacial Maximum, but to the 290 ppmv curve in the other 2 cases. This very large difference in the response of the model for the 250 ppmv CO2 level seems to indicate the existence of critical CO2 concentrations (which are time dependent) around which the climate system may be responding either like the high or like the low CO2 level.

At the Last Glacial Maximum, the 250 ppmv experiment leads to a large amount of ice, more than 30 x 106 km3, pretty close to the amount generated under the 210 ppmv forcing. This indicates that the climate system is here more resilient (less sensitive) to a CO2 increase than in the other 2 cases where the amount of ice generated under the 250 ppmv CO2 concentration is much less than under 210 ppmv (one third only). This different sensitivity of the model to CO2 around 20 kyr BP, as compared to what happens around 90 and 136 kyr BP is actually related to the state in which the climate system is before these ice maxima: the Earth is in a glacial during isotopic stages 4 to 2, whereas the climate before the other two maxima is interstadial.

In the two other cases, the amount of ice is rather low when the insolation starts to decrease and to induce the entrance into glaciation. Before the ice maximum around 136 kyr BP, there is a long ice-free interval lasting from 170 to 145 kyr BP. Similarly before the 90 kyr BP ice maximum, there is only a few million km3 of ice in the Northern Hemisphere although this period with small ice sheets is much shorter than in the previous case. Both situations requests therefore a rather low CO2 to enter into glaciation - as compared to the LGM case - preventing the 250 ppmv forcing to build sufficiently large ice sheets.

The similar behaviour of the response of the model under a 250 and a 290 ppmv forcing during all interstadials (except stage 3) confirms that its sensitivity to CO2 is different in a cold-glaciated Earth than during a warm-ice free Earth. This implies that during interglacials (like the Holocene), an ice age can be associated, in our model, only to a rather low CO2 concentration (below 250 ppmv at least).

3) At the ice volume minima dated 166, 75 and 4 kyr BP in the 210 ppmv experiment, the ice sheets disappear under the 290 and 250 ppmv CO2 concentrations and are very small for 210 ppmv. They disappear also for the 290 and even 250 ppmv CO2 concentrations between 200 and 190 kyr BP and between 125 and 118 kyr BP. All these 5 situations correspond to a 650N June insolation which peaks above 525 Wm-2 a few thousands of years earhier. The behaviour at 100 kyr BP, where the ice sheets disappear only for 290 ppmv, is different from what happened at 75 and 4 kyr BP, although the insolation is the same. This is because the previous insolation

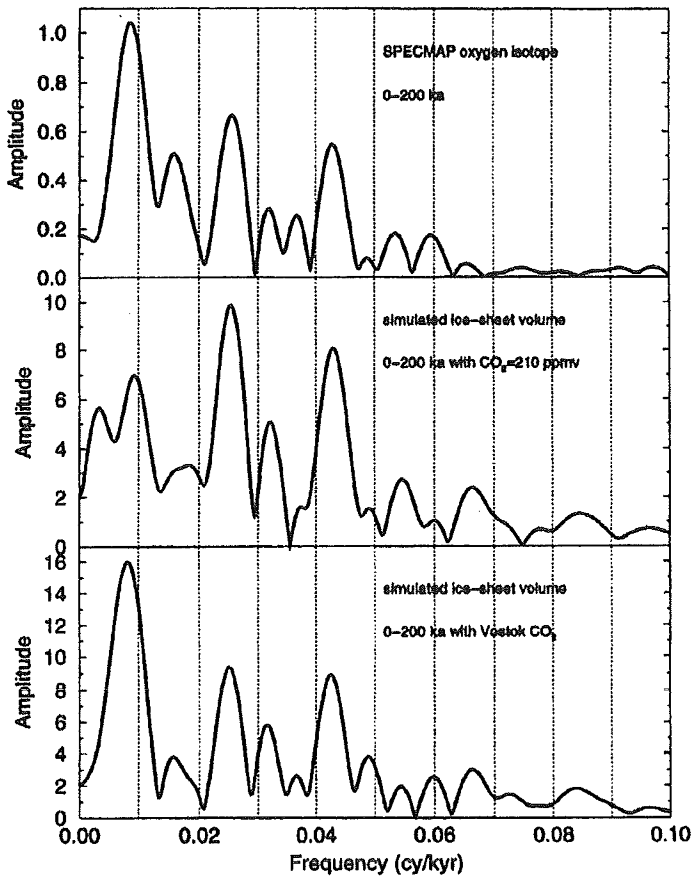

Fig. 3.: Spectra of the SPECMAP stacked curve, of the ice volume simulated by the LLN 2 - D Northern Hemisphere climate model forced by insolation and a constant CO 2 concentration of 210 ppmv (see Fig. 2 full lime) and et the ice volume simulated by the LLN 2-D Northern Hemisphere climate model forced by insolation and the Vostok CO 2 reconstruction by JOUZEL et al. (1993) from 200 kyr BP te present (Fig. 5 full lime).

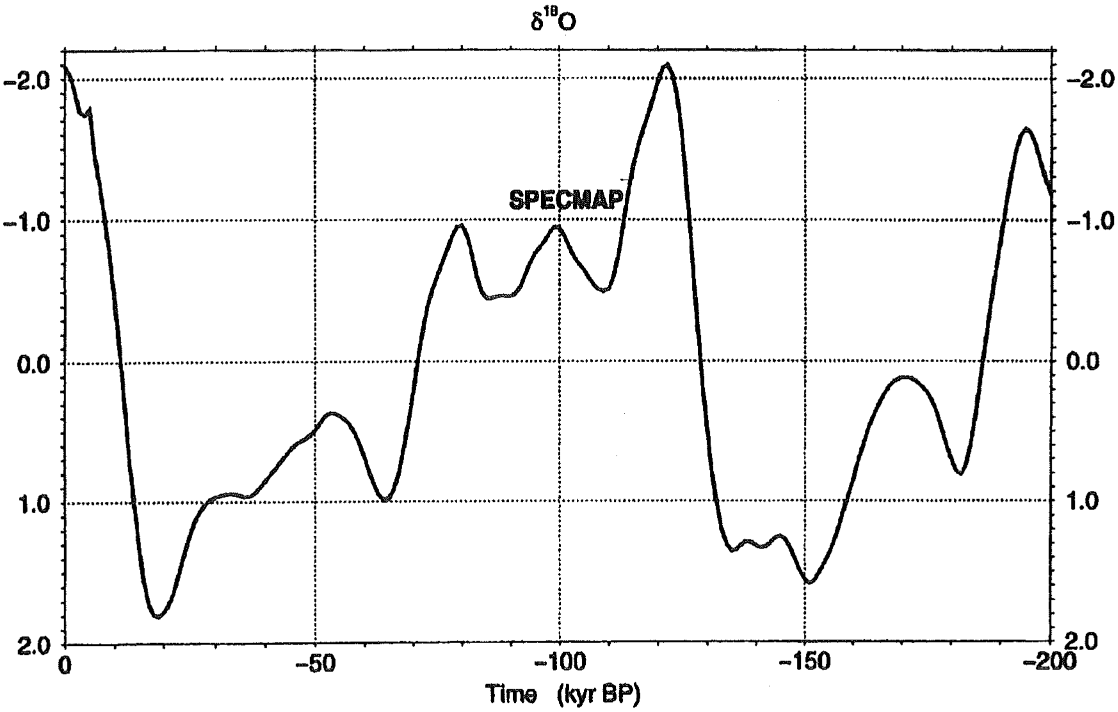

Fig. 4.: The stacked, smoothed oxygen-isotope SPECMAP record over the last 200 kyr (IMBRIE et al.,1984;MARTINSON et al., 1987).

minimum located at 116 kyr BP was much deeper than in the 75 and 4 kyr BP cases, having led to an appreciable amount of ice at 110 kyr BP.

4) In a similar way, the situation between 165 and 135 kyr BP can be associated with the situation between 50 and 20 kyr BP. Both intervals going from a minimum to a maximum of ice are exceptionally long (30 kyr) compared to the more traditional 10 kyr associated to the precession cycle. This is definitely related to the small oscillations in the insolation occurring between 170 and 140 kyr BP and between 65 and 30 kyr BP. Associated to a quite small and slowly varying eccentricity, the very weak precessional signal is unable to drive the climate system into a cycle. These cases are quite interesting for the future climate as similar situations occur quite often in the insolation of the next 100,000 years.

RESPONSE OF THE LLN MODEL TO THE INSOLATION AND CO2 FORCINGS

As there is no carbon cycle coupled to our model yet, we can only study how the response of the LLN 2-D model to the orbitally induced forcing might be modified using the reconstructed variable CO2 from Vostok (JOUZEL *et al.*, 1993) as an additional forcing to insolation. Here we assume as a first step, that using CO2 as an external forcing instead of an internally generated parameter has no significant impact on the long-term variations of climate, although it may influence the short-term response as a feedback.

Broadly speaking the response of the model under the CO2 and insolation forcings reproduce quite well the geological record.

The stacked, smoothed oxygen-isotope record of SPECMAP (IMBRIE *et al.*, 1984; MARTINSON *et al.*, 1987; Fig. 4) provides a unique record of isotopic variations over the last 800 kyr which can be compared to the simulated continental ice volume changes (Fig. 5). However, our simulations are only providing variations of the Northern Hemisphere continental ice volume. In the comparisons, we must therefore keep in mind that we do not have any reconstruction of the Southern Hemisphere ice volume (mainly Antarctica) and that a large number of hypotheses subtend the model.

The overall timing is quite well reproduced (even in the constant CO2 experiments), but discrepancies in the magnitude of the ice volume can be observed. The largest one is probably the too large ice melting simulated by the model around 170 kyr BP (even under a how CO2 forcing), although the ice volume maximum at 182 kyr BP seems to be well captured by the model. The large values of insolation around 175 kyr BP induce this important melting of the Northern Hemisphere ice sheets, a feature which remains also in the experiment using the CO2 reconstruction by JOUZEH *et al.* Either it is an important deficiency of the model or we have to look for a significant change in the Southern Hemisphere continental ice at that time. At the end of stage 6, the simulated glacial maximum occurs at 135 kyr BP whihe the δ18O ice volume maximum occurs at 151 kyr, but we must accept that the δ18O ice volume remains large from 156 to 133 kyr BP. The model simulates very well the transitions between isotopic stages 6 and 5 and between the isotopic substages 5e (Eemian interglacial) and 5d. This is due mainly to the insolation changes, but it is reinforced by important changes in the CO2 concentration. Although the timing of what may correspond to isotopic substages 5c, 5b and 5a are quite well reproduced

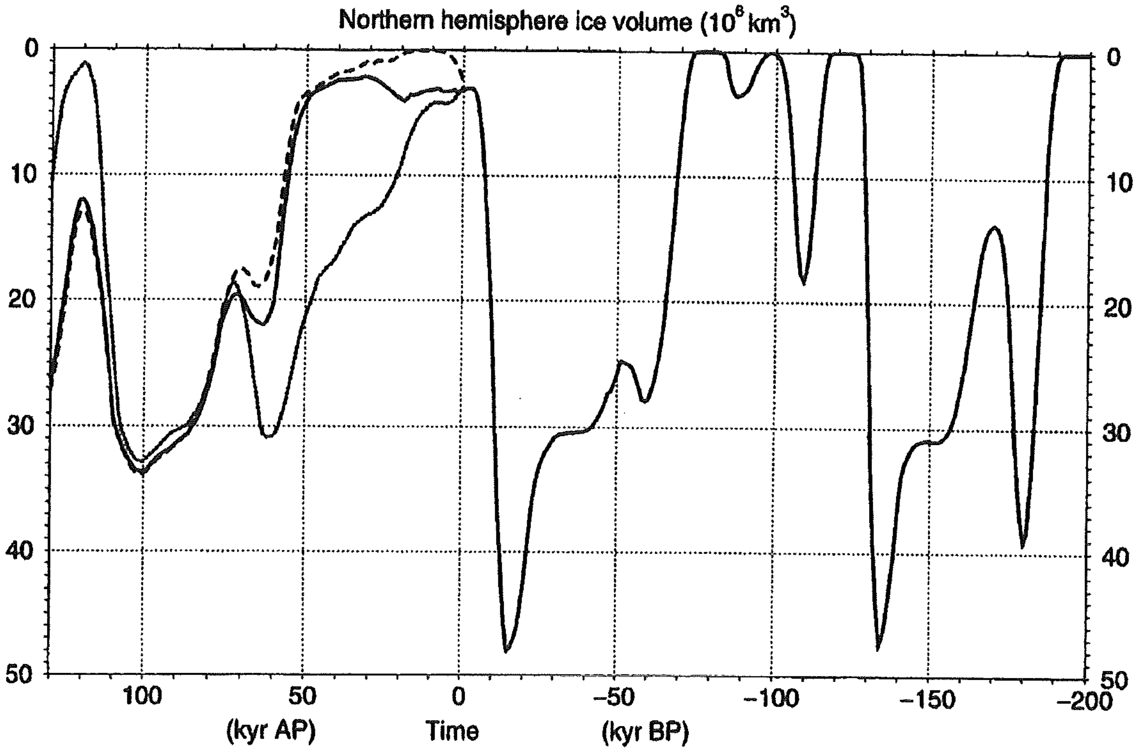

Fig. 5.: Simulated ice volume of the Northern Hemisphere using the LLN 2-D Northern Hemisphere climate model forced by insolation and CO2, from 200 kyr BP to 130 kyr AP. The atmospheric CO2 concentration at fig. 1 leads te the full line. The dotted line results from a simulation where CO2 is kept equal te 210 ppmv over the next 130 kyr and the dashed curve provides the results of the 750 ppmv scenario. Ice volume increases downward (LOUTRE & BERGER, 1997).

(a coincidence which is certainly reinforced by the astronomical tuning of the SPECMAP curve), the amount of ice is here again much less than in SPECMAP. This discrepancy is more or less similar to the one occurring at isotopic substage 6.5, 170 kyr ago. Moreover, the δ18O ice volume minimum around 90 kyr BP lasted for about 10 kyr, contrarily to the simulations, and the simulated ice volumes at stages 5a and 4 are lagging behind the δ18O curve (between 3 kyr and 8 kyr depending upon the experiments).

At 70 kyr BP, the ice sheets start to form quite rapidly to lead to a first ice volume maximum at 59 kyr BP. This is followed by a weak melting of ± 5 x 106 km3 leading to a minimum in the simulated ice volume at 50 kyr BP. The ice sheets are then starting to grow again, slowly to about 30 kyr BP and then more rapidly to the Last Glacial Maximum where they amount to 47 x 106 km3 of ice at 15 kyr BP. Stage 3 is therefore more or less well reproduced although, as for the 170 kyr BP interstadial, there is not enough ice according to SPECMAP. The simulated Last Glacial Maximum is lagging behind SPECMAP by 4 kyr, a lag which is related to the late CO2 minimum in the Vostok curve.

Finally, the model simulates a deglaciation from 15 kyr to 3 kyr BP leaving only the Greenhand ice sheet in the Northern Hemisphere with roughly 3 x 106 km3 of ice. Since 3 kyr BP, the ice volume is shown to increase slightly reaching 3.2 x 106 km3 today which represents about the present value. Our model simulation is showing that the climate has slighthy cooled since the peak of the Holocene. A similar observation is clearly visible, but over the whole last

10,000 years, in the Greenland temperature record published by JOHNSEN *et al.* (1995, see their fig. 2). Integration of the model in the future for different natural CO2 scenarios shows that the atmospheric CO2 concentration must decrease below 250 ppmv for the ice sheets to grow in the Northern Hemisphere over the next 50 kyr (LOUTRE & BERGER, 1997).

As far as the ice volume maxima are concerned, SPECMAP shows two extremes located at the Last Glacial Maximum (± 20 kyr BP) and at stage 6 (± 151 kyr BP), with the LGM being slighthy the iargest. There are also two secondary maxima, roughly of the same size: isotopic substage 6.6 (183.3 kyr BP) and stage 4 (60.4 kyr BP). The simulation using JOUZEL *et al.* CO2 reconstruction mimicks pretty well these maxima, except for the late arrival of stage 6 and an ice volume larger at stage 6.6 than at stage 4.

It is interesting to note that the Northern Hemisphere ice sheets are melting totally three times: between 126 and 117 kyr BP, 100 and 97 kyr BP and 83 and 74 kyr BP. Although this is not realistic (the Greenland ice sheet having survived; (DANSAARD *et al.*, 1993), it can be explained by the large insolation occuring at these times (as already mentioned in section 3) and the large CO2 concentration between 130 and 115 kyr BP which continues to play an important role in the behaviour of the ice sheets over the next 30 to 40 kyr.

Being given all hypotheses used in the modeling experiments, the results may be considered as surprisingly good. Using the reconstructed CO2 concentrations from deep-sea or ice cores (Fig. 5) improves the constant CO2 simulations (Fig. 2) and their spectra (Fig. 3), if SPECMAP is used as a standard for comparison. These experiments confirm that variations in the Earth's orbit and related insolation act as a pacemaker of ice ages (HAYS *et al.*, 1976) and that CO2 variations shape the 100 kyr cycle and mainly improve the simulated surface air temperature (GALLEE *et al.*, 1992; LOUTRE *et al.*, 1994). Under the astronomical forcing only, the model is able to simulate long-term variations of the Northern Hemisphere ice volume with an acceptable confidence provided the constant CO2 value used in the experiment is about 210 ppmv. Under the astronomical and CO2 forcings, the long-term variations of the simulated ice volume are in a much better agreement with the SPECMAP record.

A deeper analysis of these experiments also confirm the importance of the processes governing the response of the modelled climate system to insolation and/or CO2 changes. These are essentially related to the albedo- and water vapor feedbacks, to the taiga-tundra direct and indirect impacts on high latitudes surface albedo, to the altitude and continental effects on the precipitations over the ice sheets, to the ageing of now due to the recrystallization process and its impact on the albedo, to the lagging lithospheric response to the ice sheets loading and to the mechanical destabilisation of the ice sheets through the rapid melting of their southern front as compared to the northern one.

Based upon this validation of the LLN 2-D model over the last two climatic cycles, experiments dealing with the early and middle Pleistocene were made.

THE ENTRANCE INTO THE QUATERNARY ICE AGE

The first significant ice sheets in the Northern Hemisphere develop about 3 Myr BP when the Eurasian Arctic and Northeastern Asia entered into glaciation. Attempts have been made to explain this significant intensification of Northern Hemisphere glaciation 3 million years ago. In particular, MASLIN *et al.* (1995) proposed that it was forced by the gradual increase in the amplitude of obliquity from 3.5 to 2.5 Myr BP and a sharp rise in the amplitude of precession and thus of insolation. LI *et al.* (1998b) discussed further the possible additional influence of a progressive CO2 linear decrease from 540 ppmv to 270 ppmv between 4 and 2 Myr as suggested by SALTZMAN & VERBITSKY (1993). This 540 ppmv concentration of CO2 is closed to that deduced by CERLING (1992). In such a case, the model simulates very small short-lasting ice sheets before 3 Myr BP (Fig. 6, panel e). It is only after 2.7 Myr BP that the simulated ice sheets starts to exceed 3 x 106 km3. They are located in 3 time intervals between 3.2 and 2.9, 2.75 and 2.45 and 2.35 and 2.1. A linear regression indicate a trend of increase in the simulated ice volume from 3 Myr BP onwards with the 3 last maximum reaching 15 to 17 x 106 km3, a size which is similar to the size of the ice sheets simulated at isotopic substages 5b or 5d.

Actually the three intervals between 3 and 2 Myr BP during which the ice sheets can develop, correspond to three time intervals where the insolation (in particular in July at 650N) varies with a large amplitude (Fig. 6, panels a to d). This large amplitude of the insolation variation is related to the strong 400-kyr period which characterizes this whole one million-year interval. Moreover, from 3.5 to 2.5 Ma, the amplitude of obliquity gradually increases. Sensitivity experiments using different CO2 changes show that low summer insolation can lead to the development of the late Pliocene Northern Hemisphere ice sheets only when the CO2 concentration is sufficiently low to allow winter snow to persist from year to year. For our model, this threshold seems to be around 380 ppmv which is reached somewhere between 2.9 and 2.7 Myr BP. But the deepest summer insolation minima (of the order to 400 Wm-2 at 65°N in July) required for the ice sheets to grow occur only when the amplitude is large explaining why significant glaciation can not be initialized until 2.75 to 2.55 Myr BP. The same deep minima are also requested for generating the other corresponding glacial maximum advances at 2.33, 2.24, 2.22 and 2.13 Myr BP.

As a consequence, contrary to the late Pleistocene, the late Pliocene ice ages correspond to times of high eccentricity, which is the opposite of what happens during late Pleistocene where it is the interglacials which are related to high eccentricity. In the warm late Pliocene, the Northern Hemisphere ice sheets could develop only during very cold summers; in the colder late Pleistocene, significant Northern Hemisphere ice sheets exist during most of the time and only high summer insolation can start to melt the ice sheets and lead to an interglacial.

THE LAST 3 MYR

The relative success obtained with the LLN 2-D climate model lead to test whether it can sustain its possibility to simulate long-term climatic changes and their characteristics over a very long period, the last 3 million years. The model was therefore forced by the calculated astronomically-derived insolation (LOUTRE & BERGER, 1993) and by different CO2 scenarios. Such different atmospheric CO2 scenarios were used because of a lack of CO2 reconstruction

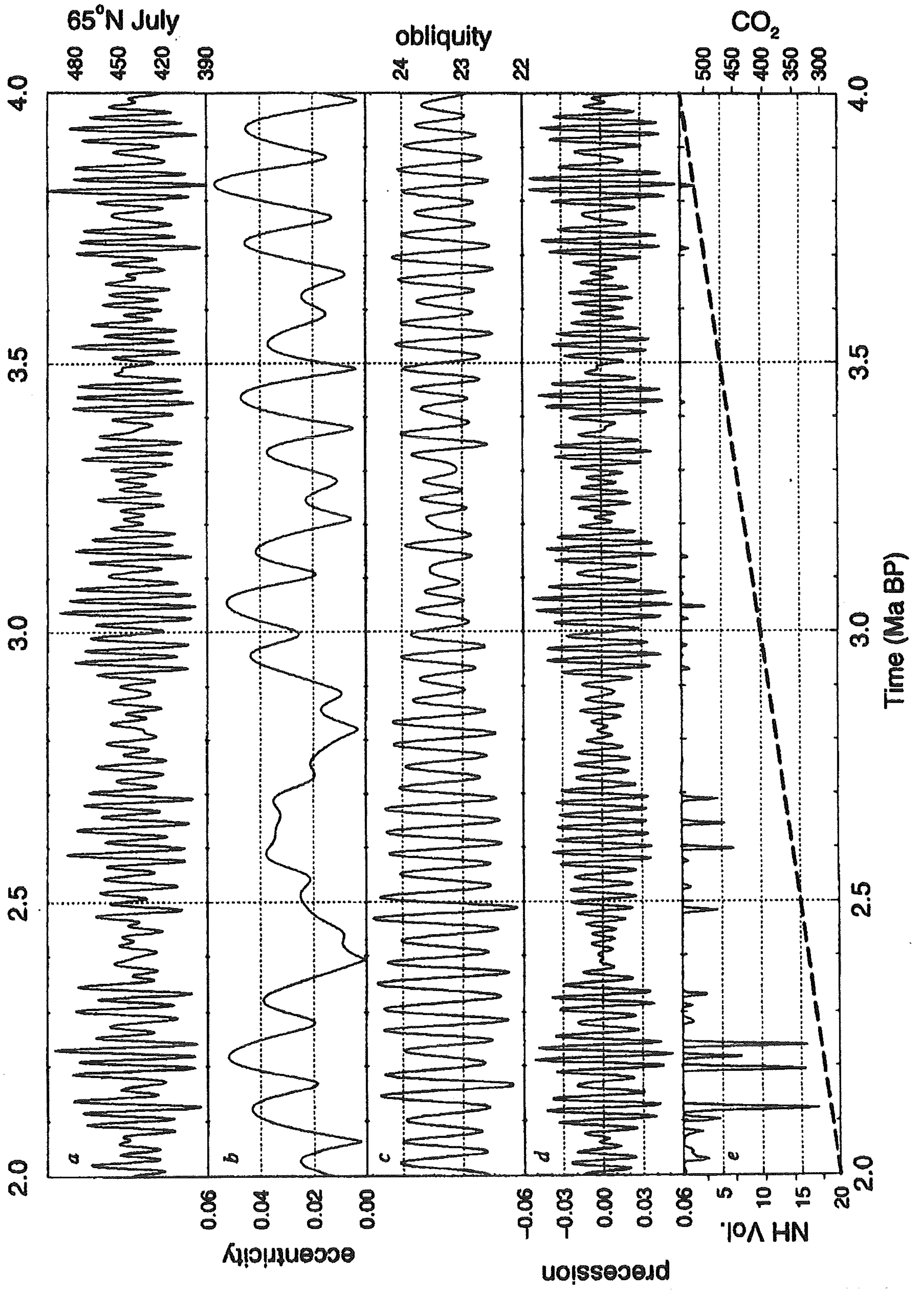

Fig. 6.: The Earth's orbital elements and the resultant insolation variation from 3.05 to 2 Myr;(a) The 65°N July insolation (Wm-2), and (b-d) the Earth's orbital parameters (LOUTRE & BEGER, 1993) and (e) simulation from 3,940 te 2 Myr (solid line), with CO2 linearly decreasing from 540 ppmv at 4 Myr te 270 ppmv at 2 myr (bold dashed line)

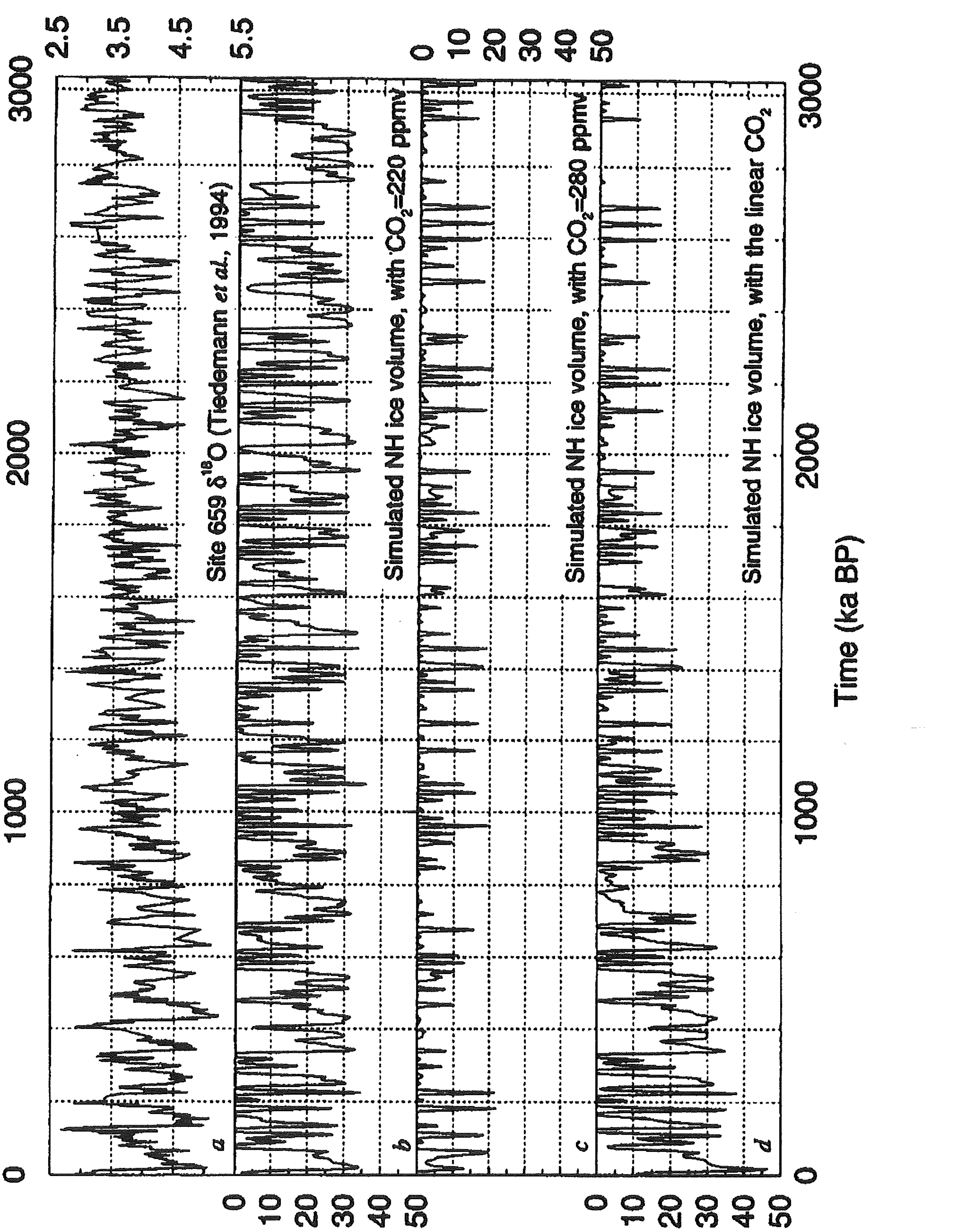

Fig. 7.: Comparison between the Site 659 8180, in 04, (TIEDEMANN et al., 1994) (a), and the simulated Northern Hemisphere ice-sheet volumes, in 106 km3, under constant atmospheric CO2 concentrations 220 ppmv (b), 280 ppmv (c), and a linearly decreasing CO2 concentration going from 320 ppmv at 3 Myr BP to 200 ppmv at the Last Glacial Maximum (d), respectively.

over this remote past. With constant CO_2 concentrations, the simulated ice volume (Fig. 7) does not show any gradual increase as recorded in the marine sediments. Moreover, its spectrum changes according to the chosen value of CO_2: when CO_2 is fixed at 220 ppmv, the simulated ice volume is dominated by the ± 100-kyr period; if a pre-industrial CO_2 concentration of 280 ppmv is used, the simulation is dominated by the ± 41-kyr period. By using a linearly decreasing CO_2 concentration going from 320 ppmv at 3 Myr BP to 200 ppmv at the Last Glacial Maximum, the simulated changes in the power spectrum are in agreement with those obtained from the sedimentary records (Fig. 8): roughly before 1 Myr BP the dominating period is ± 41 kyr, afterwards the ± 100-kyr period becomes dominant. This transition is accompanied by a gradual increase of the ice volume. Using cyclic CO_2 fluctuations over the last 0.6 Myr (see section «the last 600 KYR») does not change significantly the spectral characteristics of the simulated ice volume, but amplifies the amplitude of its variations and provides a much better fit to the geological reconstructions.

From 3 to 2 Myr BP, the intensification of glaciation at about 2.7 Myr BP is simulated, but spectral analysis for this whole period is difficult because of the long time intervals with no ice. From 2 to 1 Myr BP, the simulation has a spectrum similar to the spectrum of the $\delta^{18}O$ record, 41 kyr being the dominant period, but the duration of the warm intervals is still longer in the simulation. In timing, the simulated glaciations generally correlate to coolings in the $\delta^{18}O$ record. For example, the remarkable glaciations at 1.95 Myr, 1.78 Myr and 1.74 Myr (Fig. 7) clearly correspond to the distinct coolings in the $\delta^{18}O$ data. However, the relative magnitude of the simulated glaciations is sometimes different from the data. For instance, the glaciation at 1.21 Myr is a minor one in the simulation, and corresponds to a major cooling in the data. This deficiency can possibly be related to the rough representation of CO_2 in the simulation, but also to the structure of the model.

From the 1 Myr BP to the present, the simulation again has a spectrum similar to the geological one, and is now dominated by the 100-kyr period instead of by the 41-kyr one. Moreover, besides the similar timing for the ice waxings and wanings, the comparison in the relative amplitude between the simulation and $\delta^{18}O$ record becomes better, particularly over the last 600 kyr. For example, the ice sheets are melted (as discussed, this complete melting is not realistic but does not prevent the model from reproducing the climatic cycles) around 100, 200, 300, 500, 600 and 700 kyr BP, corresponding to the interglacials recorded in the data. The simulated glacial maxima at 0.888, 0.717, 0.628, 0.542, 0.432, 0.342, 0.251, 0.135 and 0.015 Myr can be compared to the glacial maxima in the $\delta^{18}O$ record, but a difference in the relative magnitude still exists, especially for the glacial maximum around 0.79 Myr and at stage 6. The simulated ice volume at stage 2 (46×10^6 km^3, Fig. 7) is similar to that in the 200 kyr experiment using the Vostok CO_2 (48×10^6 km^3, BERGER & LOUTRE, 1996). But at isotopic stages 11 and 1 too much ice is simulated due to the quite low CO_2 values of the linearly decreasing scenario. Using the fluctuating CO_2 concentrations reconstructed by LI *et al.* (1998a), the ice volume simulation for the two stages is improved.

In both the simulation and $\delta^{18}O$ record, the amplitude of the climatic variations generally increases with time. A key factor to explain the emergence of the 100-ka period at ±1 Myr BP is related to the warm climate characterizing the Earth before 1 Myr BP. Under a relatively high atmospheric CO_2 concentration, the Northern Hemisphere ice sheets were too small, any moderate insolation maxima could melt them and therefore stop the glaciation process. After ± 1 Myr BP, larger ice sheets started to exist during most of the time because of lower CO_2

concentrations. Under such conditions, moderate insolation maxima could reduce the ice volume slightly, but only the largest insolation maxima, occurring under high eccentricity, high obliquity and Northern Hemisphere summer at perihelion (minimum climatic precession), could lead to significant meltings of the ice sheets and therefore to interglacials, making the ± 100-kyr periodicity the most remarkable feature of climate over the time interval from 1 Myr BP to present.

THE LAST 600 KYR

This linear trend of the CO2 concentration decrease over the last 3 or 4 million years (as assumed in sections above) can only be considered as a first approach for analysing the sensitivity of the climate system to such CO2 changes. Actually deep-sea cores and ice cores show that CO2 varies quasi-periodically in relation to the astronomical forcing and in phase with the glacial-interglacial cycles. By January 1996, the drilling at Vostok site has reached 3,350 m and covers 4 climatic cycles (PETIT *et al.*, 1997). Unfortunately, the CO2 concentration which can be measured from this extended core are not yet available. This is why we have tentatively reconstructed the atmospheric CO2 concentrations over many climatic cycles from deep-sea cores (LI *et al.*, 1998a), as it was done earlier by SHACKLETON & PISIAS (1985), HOWARD (1992) and W. BERGER *et al.* (1996). This reconstruction was based upon a regression between the Vostok CO2 data and the SPECMAP oxygen isotope values over the last 220 kyr. A lag of 4.5 kyr (CO2 preceding δ18O) and a polynomial of order 5 give the best results, explaining 66 % of the Vostok CO2 variance. Assuming that the regression remains valid over the middle and late Quaternary, the reconstruction of atmospheric CO2 was extended to 600 kyr BP. This modelled CO2 is generally comparable to Shackleton and Pisias reconstruction over the last 350 kyr, to Howard up to 480 kyr BP and to W. BERGER *et al.* (1996) over the last 600 kyr. The high correlation between this W. BERGER *et al.* reconstruction and our's gives credits to using the marine δ18O record, since it is the only variable in the LI *et al.* reconstruction.

The amplitude of our CO2 reconstruction reaches 100 ppmv over the last glacial-intergiacial cycle, in agreement with Vostok data, but 60 ppmv only in earlier times, corresponding to a damping of the amplitude of the SPECMAP δ18O record. The modelled CO2 concentration is of interglacial level at stages 9 and 11, although slightly lower than at stage 5. This agrees well with the theoretical prediction of SALTZMAN & VERBITSKY (1995) which suggests also that the CO2 concentrations during stage 11 were not exceptional among the interglacial CO2 levels over the middle and late Pleistocene.

This modelled CO2 was then used to force the LLN 2-D model. The validation over the last 220 kyr allows us to use the modelled CO2 values as a good alternative of the Vostok atmospheric CO2 concentrations and to simulate the past 600 kyr using both the modelled CO2 and insolation as forcings. The simulated ice sheet volumes (Fig. 9) have good coherencies with the SPECMAP isotopic record in the main astronomical frequency bands (Fig. 10). The interglacial-glacial cycles are well reproduced. Contrary to the results obtained with a lineary decreasing CO2 (previous section), the modelled stage 11 compares well with the other interglacials despite the Northern Hemisphere high latitude summer insolation is quite low at that time. Actually our simulations show that it is not possible to generate our interglacial without the help of a high atmospheric CO2 level. This is also the case for stage 11. The current climate is, therefore, in the insolation

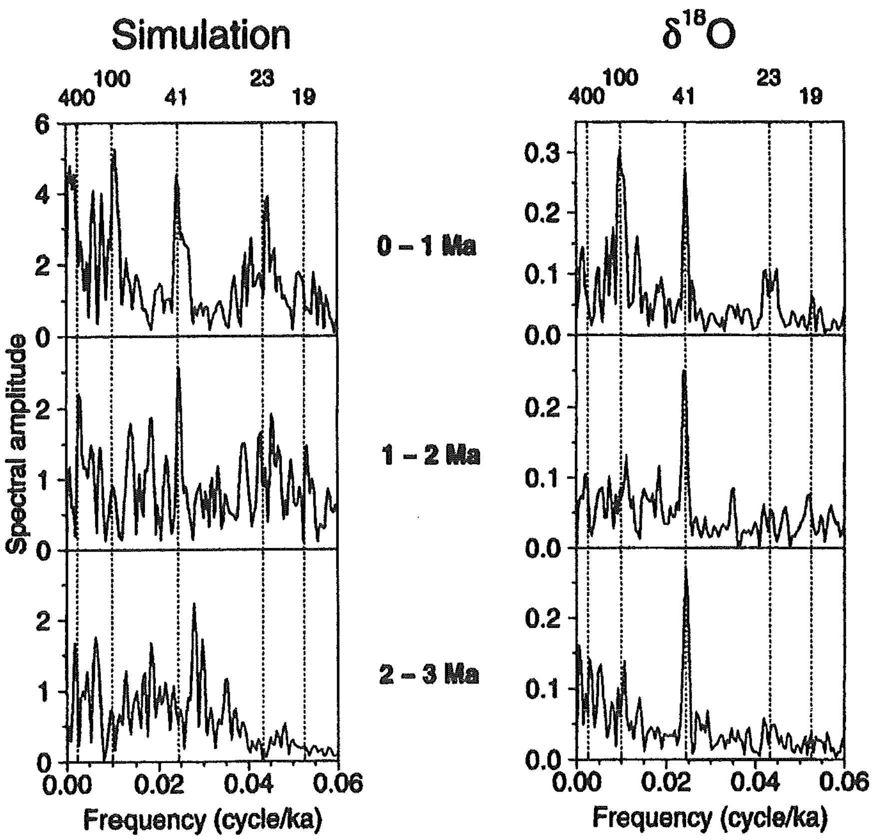

Fig. 8.: Comparison between the spectra of the simulated Northern Hemisphere ice volume represented in Fig. 7d, and of the Site 659 δ18O data (TIEDEMANN et al., 1994).

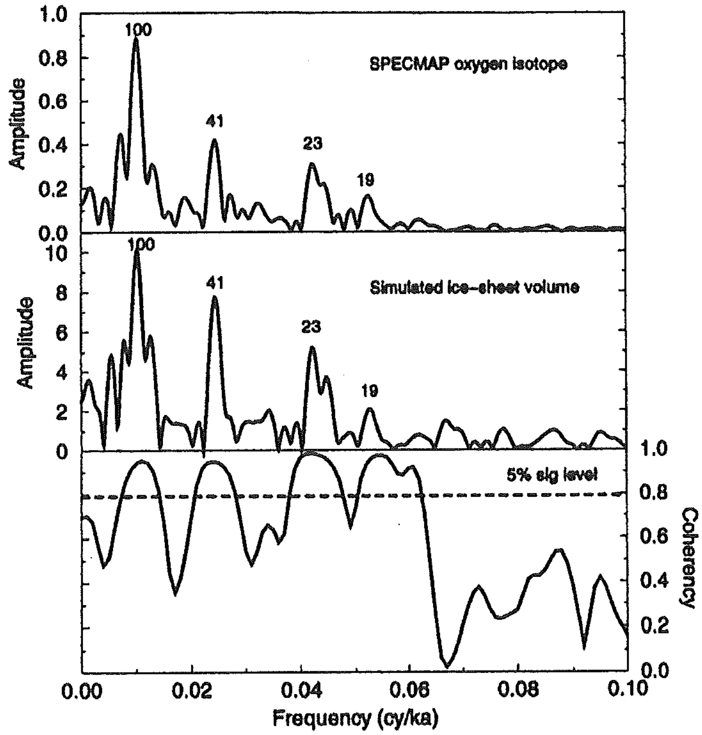

Fig. 10.: Coherency and variance spectra calculated from time series et the SPECMAP oxygen isotope (IMBRIE et al., 1984) and the Northern Hemisphere icesheet volume simulated with insolation and the modelled atmospheric CO 2 concentrations. Top and middle:spectral amplitudes in the Thomson multi - taper harmonic analysis et the oxygen isotope record and the simulated ice-sheet volumes respectively. Bottom: coherency spectrum (solid line) provided with a 5% significance level (dashed line)

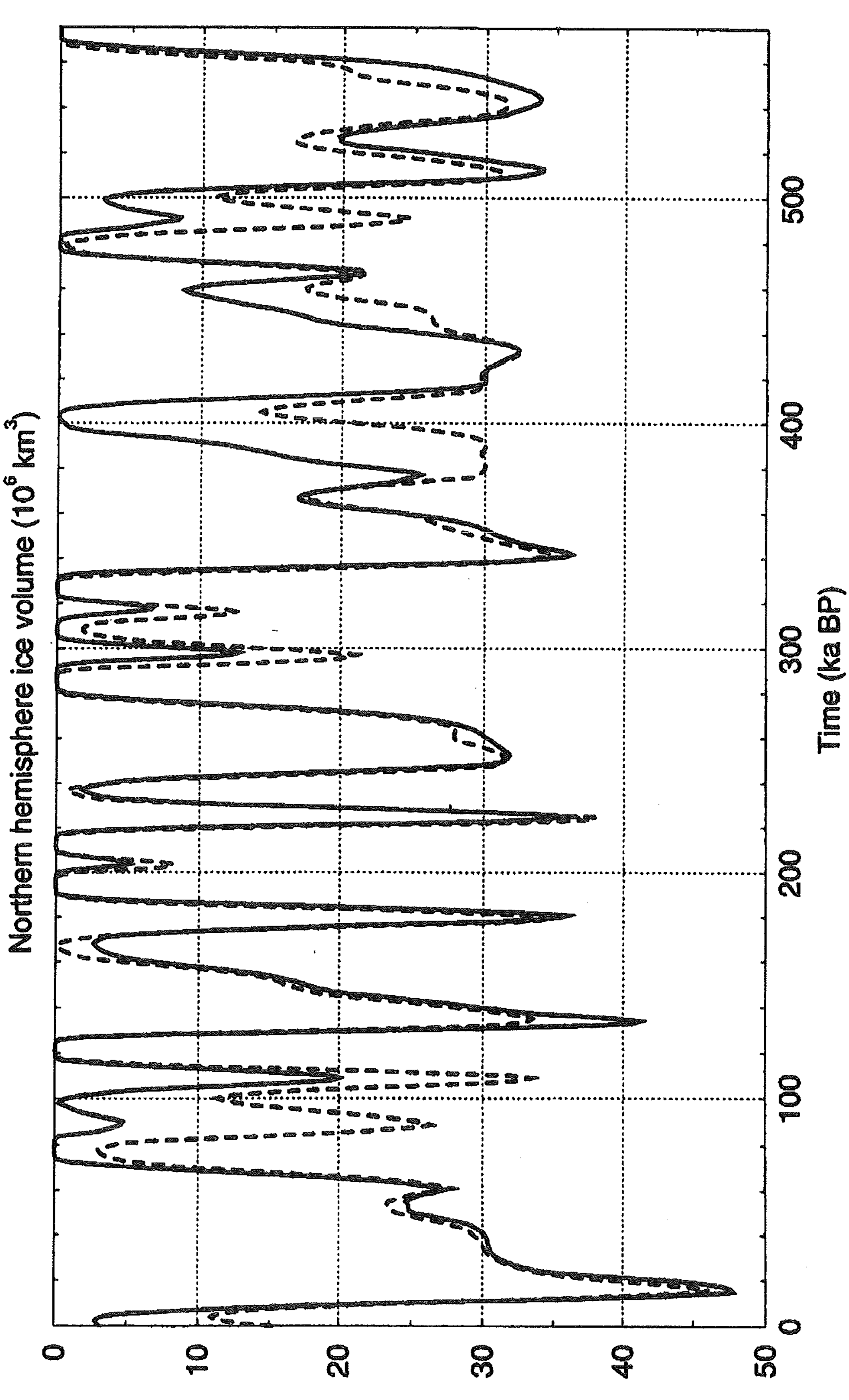

Fig. 9.: Comparison of the simulated Northern Hemisphere ice-sheet volumes over the past 575 kyr, using respectively the CO 2 concentrations reconstructed by LI et al., in 1998a (solid lime), and a linearly decreasing CO 2 (BERGER et al., 1998a, dashed lime)

and CO2 point of view, very similar to stage 11, although the Holocene CO2 level is even higher: the pre-industrial CO2 concentrations is 280 ppmv to be compared to the modelled CO2 value of 250 ppmv around 400 kyr BP. This shows that the climate at stage 11 and now is very sensitive to CO2, a matter also discussed in the next section.

THE NEXT GLACIAL-INTERGLACIAL CYCLE

INSOLATION CHANGES

The major characteristics of the insolation of the next 130 kyr is the small amplitude of its variations (Fig. 1). This amplitude is slightly increasing with time, but barely reaches 65 Wm-2 at 65°N in June, which is far less than the amplitude at isotopic stage 5 (110 Wm-2). Over the next 50 kyr, the amplitude of this insolation signal is even less than 30 Wm-2. Consequentiy, from the point of view of insolation only, the Eem can hardly be taken as an analogue of the next thousands of years, as it is often assumed.

This weak insolation variation from 5 kyr BP to 60 kyr AP is really exceptional with very few analogues in the past. Only five intervals were found to be highly correlated (correlation coefficient higher than 0.8) to this reference insolation pattern over the next 3 Myr, in particular one centered on 375 kyr BP and one centered on 1,985,000 yr BP (BERGER & LOUTRE, 1996). Because of the properties of the insolation for different latitudes and months (BERGER *et al.*, 1993a), this conclusion remains valid qualitatively whatever the month and the latitude considered.

This almost unique characteristic of insolation over the next 100 kyr is actually a result of the exceptionally low values of eccentricity which damps considerably the amplitude of the variations of precession (BERGER *et al.*, 1998c). This situation reinforces the role of obliquity and influences the length of the cycle. If the small oscillation occuring between 28 and 41 kyr AP is neglected, the distance between the insolation minima at 17 kyr AP and 54 kyr AP amounts 37 kyr (which can reach 53 kyr if we by-pass the 10 Wm-2 oscillation between 9 and 17 kyr AP).

It happens that we are presently in a minimum phase of the 400-kyr cycle of eccentricity. The transition between the last and the next 400-kyr cycles is characterized by a short cycle (at the (100-kyr)-1 frequency) with a low amplitude which is very similar to those centered at ± 800 kyr BP and 400 kyr BP. The distance separating two successive minima of the eccentricity is 64 kyr between 437 and 373 kyr BP and 70 kyr between 43 kyr BP and 27 kyr AP. This has a direct influence not only on the amplitude of precession, but also on the length of its cycle. It is possible to show that at the 400-kyr time scale, the modulations in amplitude and in frequency of precession are inversely related: to a low eccentricity value corresponds a short period. From 47 kyr BP to 77 kyr AP, the time interval between successive maxima decreases progressively from 25 kyr to 16 kyr (which occurs between 18 and 34 kyr BP) and increases again to reach 23 kyr (between 54 and 77 kyr AP). For obliquity, the amplitude is decreasing over the next 30 kyr because we are at the end of a particularly long cycle of its modulation (190 kyr to be compared to an average of 166 kyr). From 29 kyr BP to 10 kyr AP, the present-day cycle of obliquity is below normal (39 kyr) and will slowly increase to 41 kyr over the next 100 kyr.

RESPONSE TO CONSTANT CO2

Three constant CO2 concentrations were first used as external forcing, in addition to the insolation (BERGER & LOUTRE, 1996, 1997): a low value (210 ppmv), a high value (290 ppmv) and a medium value (250 ppmv) as in section 3. These experiments are sensitivity experiments to estimate the relative importance of the astronomical forcing and of the CO2 concentration for simulating future ice ages.

Over the next 130 yr June insolation at 65N is most of the time larger than 470 Wm-2. Consequently no ice-sheet can develop under high, CO2 concentration (290 ppmv). The Northern Hemisphere continental ice volume remains always lower than the present-day and most of the time there is no ice-sheet. However, when CO2 is low (210 ppmv), the ice sheets do appear over the next 130 kyr (Fig. 5). The ice volume increases up to 58 kyr AP where it reaches 32x106 km3 and the following glacial maximum is reached at 101 kyr AP with this same amount of ice. These two ice volume maxima are following two insolation minima at 59 and 97 kyr AP, each of them appearing after a weak maximum. There is an interstadial at 72 kyr AP, and a short interglacial peaking at 120 kyr AP, both related to an insolation increase. In the 250-ppmv experiment there are also two glacial maxima (at 63 and 106 kyr AP), but they are delayed when compared to the 210-ppmv experiment, they are characterized by smaller ice volumes, the interstadial lasts much longer (from 75 to 100 kyr AP), and at the end of the simulation (from 115 kyr AP to 128 kyr AP) the ice sheets are completely melted.

During the whole interval from 20 to 110 kyr AP, the difference between the ice volumes generated under a 210 and a 290 ppmv forcing is very large. This seems to be due to the very weak amplitude of the insolation change which let the climate system to be very sensitive to the atmospheric CO2 concentration. This is not the case for the Eemian times where the simulated ice sheets melt for all three CO2 constant values (Fig. 2). This reflects a higher sensitivity of the model to CO2 when the insolation variations are small (now and in the future) than when they are large (Eem). This conclusion, if confirmed by experiments with more sophisticated models, maybe very important in the framework of the intensitification of the greenhouse effect due to man's activities.

A NATURAL VARYING CO2 SCENARIO

But past CO2 concentration has undergone large variations and there is no reason why it should not be the case for the future. Consequently, it was decided to use the past CO2 variations reconstructed by JOUZEL *et al.* (1993) as another approximation for the future (BERGER & LOUTRE, 1996, 1997). This reconstructed time series was shifted toward the future by 131 kyr, in such a way that the CO2 value at the initial stage of the integration coincides with the present-day value of the reconstruction. However, the atmospheric CO2 concentration is, in some complicated ways, related to climate; this scenario can therefore introduce some incoherences between the orbitally-forced climatic changes and the CO2 forcing, a remark which is strengthened by the fact that the insolation over the last glacial-interglacial cycle is not an analogue for the future.

Under such a natural scenario, the ice volume simulated by the LLN 2-D model, starting with the present-day Greenland ice sheet, leads first to an interglacial which is exceptionally long (Fig. 5). The peak of this interglacial lasts ± 55 kyr (from 5 kyr BP to 50 kyr AP), which is rather unusual when compared to the more traditional 10 to 20 kyr found in geological records (KUKLA *et al.*, 1972, 1997). This characteristic is related to the small changes in insolation described above and a CO2 concentration which remains larger than 270 ppmv over the next 20 kyr. In a warm world - like in the late Pliocene - LI *et al.* (1998b) have shown that a high eccentricity is requested to force high latitudes summer insolation to become particularly low during the negative phase and minimum of precession and so, to initiate a glacial. This is exactly the reverse of what is observed during the late Pleistocene glacial world where a high eccentricity is usually associated to an interglacial (HAYS *et al.*, 1976). This means that, if for one reason or another, the CO2 atmospheric concentration remains high at the geological time scale, the future of the Holocene might look much more like the late Pliocene (or even earlier warm periods like the Pliocene, the Paleocene-Eocene boundary and the Mid-Cretaceous although the significantly different geography at these remote times prevent to use them as "analogs" for the next hundreds of thousands of years (CROWLEY, 1990). Starting 50 kyr AP, there is a global trend of growing ice sheets with a short reversal which lasts roughly 10 kyr. The first maximum of ice occurs at 63 kyr AP with 22 x 106 km3, a maximum which is partly due to the important decrease of CO2 which started at 57 kyr AP. It is followed by a secondary minimum at 71 kyr AP with 20 x 106 km3 of ice and a maximum of 33 x 106 km3 at 100 kyr AP, before deglaciation starts.

With all the cautions required by the quite arbitrary nature of the CO2 scenarios and by all the hypotheses of the model, we can expect that the robustness of the simulated ice volume over the next 130 kyr pleads for it to be considered as a reference for the natural evolution of climate at the geological time-scale, (at least before simulations with more complete models become available). Within this framework, it was worth testing the sensitivity of this natural evolution to what may happen to the climate system over the next few centuries to millenia.

THE POSSIBLE HUMAN IMPACT

Let us first note that, according to the reconstructed CO2 concentration over the last two glacial-interglacial cycles, 290 ppmv is reached only during very limited times. Most of the time, the CO2 concentration is situated around 225 ppmv (between 210 and 250 ppmv). Assuming a constant CO2 concentration of 250 ppmv over thousands of years (as we did in section: Response to constant CO2) is therefore already a very strong forcing of the climate system, if we refer to the last 250,000 years. This is why two other long-term CO2 scenarios were constructed during which high CO2 values will be kept over much shorter times (LOUTRE & BERGER, 1997). They are based upon the IPCC scenarios leading respectively to a stabilized CO2 concentration of 750 and of 550 ppmv between the XXIInd and the XXIIIrd centuries (HOUGHTON *et al.*, 1996). Currently it is assumed that the CO2 concentration wil increase from the unperturbed level (assumed to be 296 ppmv in the model) to 750 or 550 ppmv over the next 200 years, will decrease to 300 ppmv over the following 450 or 300 years, will reach linearly the 1 kyr AP concentration of the natural scenario of section «Natural varying CO2»and will then follow this scenario up to 130 kyr AP.

The responses of the Northern Hemisphere ice sheets to these scenarios are very different. In the 550 ppmv experiment, a slight melting of the Northern Hemisphere ice occurs only over the next 1,000 years and it is very difficult to see any difference with the results from the natural scenario based upon the Vostok data. For 750 ppmv, the impact is far more pronounced, a complete melting of the Greenland ice sheet being simulated between roughly 10 and 14 kyr AP. These results seem to indicate that there is a threshold value of CO2 above which the Greenland ice sheet disappears in the LLN 2-D model. The melting of the Greenland ice sheet itself is not the important result and can not be stressed being given the simple ice-sheet model used (BERGER *et al*, 1990). What is interesting is only the broad characteristics of the results obtained. In particular, with the same CO2-Vostok forcing the model simulates an ice-free Northern Hemisphere at the peak of the Eem but not at the Holocene. The different isotopic stages 5 are modelled in pretty good agreement with the geological record (MARTINSON *et al.*, 1987). However, the simulated Northern Hemisphere ice sheets disappear totally during the isotopic stages 5e, 5c and 5a which is not recorded in the Greenland ice record (DANSGAARD *et al.*, 1993). This weakness of the model reveals a high sensitivity to the insolation forcing, but does not affect qualitatively the overall reconstruction of the glacial-interglacial cycles.

A detailed analysis of the contribution of the individual ice sheets to the total northern hemisphere ice volume shows that it is dominated by the Greenland ice sheet up to 50 kyr AP. At this date, the Eurasian ice sheet starts to grow significantly, followed by the Northern American ice sheet a few thousands of years later. As in other experiments made by LOUTRE & BERGER (1997), the human burst of CO2 during the XXth to XXIInd centuries seems to be sufficient to lead to a melting of the Greenland ice sheet in the LLN model. This is occuring under a constant CO2 concentration larger than 290 ppmv (with a melting from 30 to 55 kyr AP) and even in the 750 ppmv scenario where the CO2 concentration is supposed to reach back 300 ppmv as soon as at 650 yr AP and from this time onwards, to return to the natural scenario (the total melting then occur between 8 and 15 kyr AP).

The simulated ice volume in the 750 ppmv scenario are almost the same as in the natural scenario after 40 kyr AP. After 100 kyr AP, the natural, the 550 and the 750 ppmv scenarios lead to more or less similar results. It seems therefore that 40 kyr at least are required for the climate system to be no longer sensitive to what could happen over the next few centuries.

CONCLUSIONS

A series of experiments have been made with the LLN 2-D Northern Hemisphere climate model to test its sensitivity to both the astronomical and the CO2 forcings. We must keep in mind that our model has still to be improved: some processes are missing or are crudely represented, such as the ocean dynamics, the cloud-climate feedback and the hydrological cycle. For all the CO2 scenarios used (constant or reconstructed CO2) CO2 is considered as an external forcing. Consequently changes in CO2 induce changes in many climatic variables and trigger the albedo and water vapor feedbacks, but the climate does not feedback on CO2 concentration (through vegetation for example). A deeper analysis of these weaknesses is continuously underway and an improved and extended version of the LLN model, considering both hemispheres, three oceanic basins and a more realistic hydrological cycle is in progress. The two main conclusions that we may draw are related to the confirmation that variations in the Earth's orbit and related insolation act as a pacemaker of ice ages and to the influence of CO2 variations for shaping the 100 kyr cycle and mainly for improving the simulated surface air temperature.

Based upon the validation of the model over the past 3 Myr, its response to future insolation and CO2 was investigated. All the experiments done show that we are facing an exceptionaliy long interglacial. Except for scenarios where the CO2-concentration is kept constant below 215 ppmv, our Holocene Interglacial is predicted to last up to 50 kyr AP.

On the basis of limited evidence available, GOODNESS *et al.* (1992) and BERGER *et al.* (1991) first concluded that, following a period of warming, the next glaciation will just be delayed and less severe. However, the experiments described here show that the future climate behaviour is very sensitive to the greenhouse gas concentrations and to their hypothetical changes in time. According to these new results, the enhanced greenhouse warming might weaken the positive feedback mechanisms which transform the relatively weak orbital forcing into global interglacial-glacial cycles, so that the initiation of future glaciations will be prevented (i.e. the cooling trend towards the next ice age delayed by tens of thousands of years). In such conditions, a kind of so-called "irreversible greenhouse effect" could become the most likely future climate. At least our result confirms the prediction of Murray Mitchell Jr in 1972: "The net impact of human activities on the climate of the future decades and centuries is quite likely to be one of warming and therefore favorable to the perpetuation of the present interglacial".

However, all these results have to be confirmed by other more sophisticaded models. In particular, it is important to test whether or not global warming could trigger a sudden and sharp cooling in the northern middle and high latitudes as suggested by RAHMSTORF (1994) and to analyse whether this cooling can extend to the whole Earth and/or be sustained at the geological time scale.

Nevertheless, modelling results confirm more and more that the pattern and range of global climatic conditions likely to be experienced over the future will be close to those experienced during some Quaternary warm phases, the late Pliocene or even at the Paleocene-Eocene boundary. It is therefore more than reasonable to use the reconstructed record of past climates to test our model-understanding of the behaviour of the climate system and as a guide to future conditions. In any case, these studies provide at least some indication on how future climatic evolution may diverge from past one because of enhanced greenhouse warming.

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