

Modelling Sequential
Biosphere Systems
under Climate Change
for Radioactive
Waste Disposal

EC-CONTRACT : FIKW-CT-2000-00024

Deliverable D3:

Global climatic features over
the next million years and
recommendation for specific
situations to be considered



Work package 2: Simulation of the future evolution of the biosphere system using the hierarchical strategy

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Foreword

The BIOCLIM project on modelling sequential BIOSphere systems under CLIMate change for radioactive waste disposal is part of the EURATOM fifth European framework programme. The project was launched in October 2000 for a three-year period. The project aims at providing a scientific basis and practical methodology for assessing the possible long term impacts on the safety of radioactive waste repositories in deep formations due to climate and environmental change. Five work packages have been identified to fulfil the project objectives :

Work package 1 will consolidate the needs of the European agencies of the consortium and summarise how environmental change has been treated to date in performance assessments.

Work packages 2 and 3 will develop two innovative and complementary strategies for representing time series of long term climate change using different methods to analyse extreme climate conditions (the hierarchical strategy) and a continuous climate simulation over more than the next glacial-interglacial cycle (the integrated strategy).

Work package 4 will explore and evaluate the potential effects of climate change on the nature of the biosphere systems.

Work package 5 will disseminate information on the results obtained from the three year project among the international community for further use.

The project brings together a number of representatives from both European radioactive waste management organisations which have national responsibilities for the safe disposal of radioactive waste, either as disposers or regulators, and several highly experienced climate research teams, which are listed below.

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Content List

1- Introduction	6
2 - CO₂ Scenarios	7
2.1 - Fossil fuel contribution	7
2.1.1 - Working hypothesis	7
2.1.2 - Global carbon cycle modelling	7
2.1.3 - Carbon dioxide emission scenario	8
2.1.4 - Atmospheric concentration of carbon dioxide	9
2.2 - Future natural variations in atmospheric carbon dioxide	9
2.2.1 - Regression model	9
2.2.2 - Threshold model	10
2.3 - Combined natural variations and fossil fuel contribution	11
3 - Climate simulations	12
3.1 - Description of the simulations	12
3.2 - The forcings	13
3.2.1 - Insolation	13
3.2.2 - CO ₂ concentration	14
3.3 - Results	15
3.3.1 - Northern Hemisphere continental ice volume	15
3.3.2 - Northern Hemisphere annual mean surface temperature	19
4 - Recommendations	20
5 - References	27



1. Introduction

The BIOCLIM project aims at assessing the possible long-term impacts of climate change on the safety of waste repositories in deep formations using climate simulations of the long-term climate in various European areas. One of the objectives of the project is to develop two strategies for representing sequential climatic changes to the geosphere-biosphere system for different sites over Europe, addressing the time scale of one million years. The results of this work will be interpreted in terms of global or regional changes of climate and of vegetation. The first strategy (hierarchical strategy) will use the full hierarchy of existing climate models (a climate model is a numerical simplified representation of the climate system behaviour and evolution). Simple models (LLN 2-D NH and threshold models; see the description here after) will simulate the overall long-term evolution of the global climate. Their results will then be used as inputs to more complex models (LMD climate models possibly coupled with vegetation models, either SECHIBA or ORCHIDE) and finally climate and vegetation cover will be determined for specific sites at specific times. A second strategy (integrated strategy) will consist in building an integrated climate model, which represents most of the physical mechanisms for studying long-term climatic variations. The results will then be interpreted on a regional scale. This deliverable is the first step of the hierarchical strategy. The purpose of this deliverable is to identify and justify some specific climatic situations amongst different long-term simulations that are of interest for assessing the safety of radioactive waste repository sites and that will be further studied with GCMs (General Circulation Model).

The simple threshold (or multi-state) climate model is a modified version of the model from Paillard [Ref. 11]. It describes the time evolution of the ice volume and the CO₂ concentration. It has two distinct regimes (interglacial and glacial). The ice volume is relaxed to zero during the interglacial regime and there is no relaxation term during glacial regime. In both regimes

the forcing is a function of a smoothed truncation of the insolation and of the obliquity. Similarly, the CO₂ concentration is relaxed towards prescribed values, according to the regime and the forcing. As for ice volume the forcing is a function of insolation and obliquity. The transition between the different regimes occurs when insolation (Northern Hemisphere Summer solstice at 65N and March equinox at 40S), obliquity and ice volume cross prescribed thresholds. It must be noted that in this model CO₂ concentration does not act on climate. This model reproduced reasonably well the succession of glacial-interglacial cycles over the late Pleistocene. Such model can only account for the natural state of the climate system and not for the potential human impact on climate.

The LLN 2-D NH (two-dimension Northern Hemisphere) climate model developed in Louvain-la-Neuve has been used to simulate the global climate change over the next one million years (section 2). The primary forcing of this model is the computed latitudinal and seasonal distribution of insolation linked to orbital variations. The atmospheric concentration of CO₂ plays an important role in modifying the amplitude of the long term climatic response to solar forcing. Natural CO₂ variation is an integral component of the biosphere system. However, the model does not include a full carbon cycle that would allow the atmospheric CO₂ concentration to be internally computed. Besides, human activities also introduce additional greenhouse gases (including CO₂) into the atmosphere from fossil fuel burning. Therefore, various alternative scenarios of the future greenhouse gas concentration have been identified and are considered as an external forcing mechanism. Some scenarios for the future atmospheric CO₂ concentration are presented in Section 2 and have been used in the LLN 2-D NH climate model to simulate the climate evolution of the next 1 million years (Section 3). Recommendations for snapshot experiments to be performed with the GCM are presented in Section 4.



2. CO₂ scenarios

2.1. - Fossil fuel contribution

2.1.1 - Working hypothesis

Several considerations govern the choice of a suitable CO₂ scenario:

- a) It should be based on a physically realistic model of global carbon reservoirs and transfers;
- b) When driven by estimated historical releases of carbon dioxide from fossil fuel consumption, it should yield present-day atmospheric carbon dioxide concentrations consistent with observations;
- c) It should be consistent with the spectrum of IPCC emissions scenarios used in the Third Assessment Report [Ref. 1] throughout the period for which such scenarios are available;
- d) It should be consistent with known economic reserves of coal, oil and gas;
- e) It should result in peak atmospheric concentrations of carbon dioxide that are consistent with reversion to glacial-interglacial cycling when these concentrations eventually reduce to near natural

levels because safety cases should be robust across as wide a range of climatic conditions, going from full glacial to super-interglacial.

The last point strongly favours carbon dioxide emission scenarios toward the lower end of the IPCC range, as scenarios toward the higher end lead to peak atmospheric carbon dioxide concentrations that have considerable potential to induce gross instability in the Greenland and Antarctic ice sheets. Whether glacial-interglacial cycling would resume subsequent to the substantial collapse of these ice sheets, notably the Antarctic ice sheets, has not been determined.

Indeed, it should be recognised that even scenarios toward the low end of the IPCC range will force the climate system into a state for which there is no analogue throughout the whole of the Quaternary. Therefore, even in these scenarios, a reversion to glacial-interglacial cycling cannot be guaranteed.

2.1.2 - Global carbon cycle modelling

There have been only a limited number of studies that have attempted to estimate future atmospheric carbon dioxide concentrations on timescales of a millennium or longer. An early study was that of [Ref. 2]. This gave time-dependent concentrations on timescales of several millennia for high and low fossil fuel utilisation scenarios. These scenarios resulted in peak atmospheric concentrations of up to about 1600 ppmv carbon dioxide, with the peak concentrations occurring a few hundred years in the future.

Subsequent to the work of Sundquist, Walker and Kasting [Ref. 3] described a model that took into account fossil fuel consumption, changes in global forest cover and the fertilisation effect of increased concentrations of atmospheric carbon dioxide. Various scenarios of fossil fuel utilisation and forest clearance led to peak atmospheric carbon dioxide concentrations of between 1000 and 2000 ppmv at about 300 to 700 years AP.

Archer et al. [Ref. 4; Ref. 5] provide a model-based relationship between the amount of carbon introduced instantaneously into the atmosphere as carbon dioxide (in units of Gigatons of carbon, GtC) and the time-dependent amount of carbon dioxide in the atmosphere in GtC. This latter quantity is readily converted into a concentration in ppmv.

More specifically, Archer et al. [Ref. 4] gives an instantaneous response function for atmospheric carbon dioxide of the form:

$$\begin{aligned} \text{atmCO}_2(t) = & \\ \text{atmCO}_2(0) + 3000[& 0.75 \times \exp(-t/365) \\ & + 0.135 \times \exp(-t/5500) \\ & + 0.035 \times \exp(-t/8200) + 0.08 \times \exp(-t/200000)] \end{aligned}$$

where t is time given in year.

This is expressed in terms of the total mass of carbon

dioxide in the atmosphere and is for a single instantaneous injection of 3000 GtC. The pre-industrial amount of carbon dioxide in the atmosphere was 625 GtC and this corresponded to 280 ppmv. The response function for injection of 1 GtC, expressed in terms of CO_2 concentration in ppmv (denoted $[\text{CO}_2]$) can be written as:

$$\begin{aligned} [\text{CO}_2(t)] = & \\ [\text{CO}_2(0)] + (280/625) [& 0.75 \times \exp(-t/365) \\ + 0.135 \times \exp(-t/5500) & + 0.035 \times \exp(-t/8200) \\ + 0.08 \times \exp(-t/200000)] & \end{aligned}$$

To compute the time-dependent atmospheric concentration of carbon dioxide, it is necessary to convolute the above function with an appropriate time series of past and future releases of carbon dioxide to the atmosphere from fossil fuel consumption. Derivation of such a time series is addressed in the next section.

2.1.3 - Carbon dioxide emission scenario

Although not strictly correct, it was practicable to assume that negligible releases of carbon dioxide from fossil fuel combustion occurred before 1850. The pre-industrial observed atmospheric concentration of CO_2 of 280 ppmv was taken to be applicable before that date and also to be the baseline value applicable after that date upon which the contribution from fossil fuel combustion had to be imposed. The issue of accounting for time variations in the concentration of natural carbon dioxide is discussed further below.

By 1950, the concentration of atmospheric carbon dioxide had risen to around 300 ppmv and by 1999 the concentration was approximately 370 ppmv. As 280 ppmv corresponds to an atmospheric load of 625 GtC [Ref. 4], if losses to long-term reservoirs are neglected, the increased CO_2 concentration would correspond to injections to the atmosphere of about 40 GtC between 1850 and 1950 and 160 GtC between 1950 and 1999.

For the period 1990 to 2100, the various IPCC TAR (Third Assessment Report) emissions scenarios give cumulative emissions of between about 700 and 2600 GtC, with a central value of around 1500 GtC [Ref. 6]. As economic reserves are estimated to be around 5000 GtC [Ref. 4], it seems reasonable to adopt low and central IPCC scenarios, but to prolong those scenarios until a substantial fraction of the total economic reserves have been exhausted.

On the basis of the above, the period from 1850 to 2100 has been subdivided into three components. From 1850 to 1950, the emission rate was taken to increase linearly from 0.0 to 0.8 GtC/y, giving total emissions over the period of 40 GtC. From 1950 to 2000, the rate was taken to increase linearly from 0.8 to 5.6 GtC/y, giving total emissions over the period of 160 GtC. From 2000 to 2100, the rate was taken to increase linearly from 5.6 GtC/y to either 14.4 GtC/y or 24.4 GtC/y, giving total emissions over the period of either 1000 or 1500 GtC.

After 2100, it seems likely that emission rates would not decrease for some time, but would eventually begin to decline as restrictions on usage were imposed or costs began to rise. A simple scenario is assumed, with rates continuing at their 2100 values to 2200 and then declining linearly to zero from 2200 to 2300. This gives total emissions over the period 2100 to 2300 of either 2160 GtC or 3660 GtC, depending on whether the emission rate at 2100 is 14.4 or 24.4 GtC/y.

In the two scenario variants (further called low and high scenarios), total emissions over the period 2000 to 2300 are 3160 or 5160 GtC. These values are broadly consistent with current estimates of economic resources.

2.1.4 - Atmospheric concentration of carbon dioxide

Convolution of the variant emissions scenarios described in Section 2.1.3 with the Archer et al. [Ref. 4] response function described in Section 2.1.2 allows the time-dependent atmospheric concentrations of carbon dioxide to be calculated.

First, the fossil fuel contribution to atmospheric carbon dioxide concentrations is added to a natural concentration that is held fixed at the immediately pre-industrial value of 280 ppmv. Results for the two variant scenarios are illustrated in Figure 1.

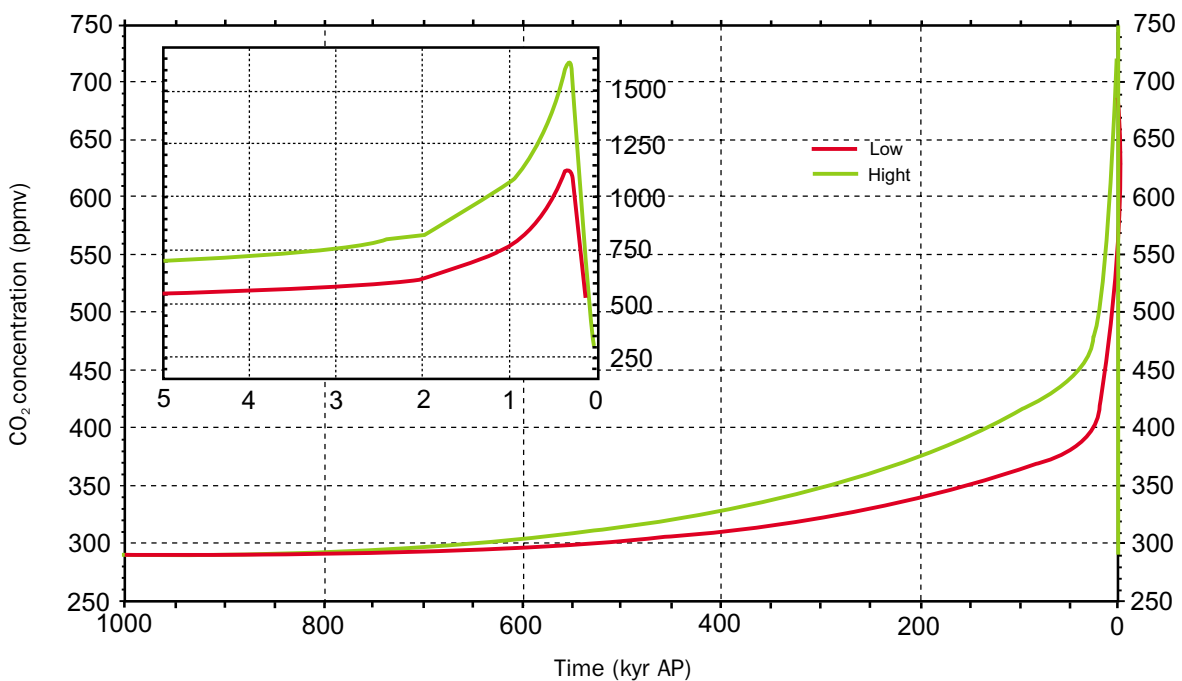


Figure 1: Scenarios of atmospheric carbon dioxide concentration over the next 1 million year (1000 kyr). These scenarios assume fossil fuel contribution on the top of a natural constant CO₂ concentration (280 ppmv). The inset panel is a blow-up of these scenarios for the next 5 kyr.

2.2. - Future natural variations in atmospheric carbon dioxide

2.2.1 - Regression model

Gas composition data from inclusions in the Vostok ice core [Ref. 7; Ref. 8; Ref. 9] have demonstrated that atmospheric carbon dioxide concentrations varied substantially during the last glacial-interglacial cycle. In his thesis, Burgess [Ref. 10] developed a regression between insolation variables and the Vostok record of atmospheric carbon dioxide concentrations. This regression was based on the odd years during the period 1-125 kyr BP. It was used as a transfer function to predict natural changes in atmospheric CO₂ concentrations over the next 150,000 years using calculated insolation values. The regression equation is given by :

$$\begin{aligned}
 [\text{CO}_2] = & (296.8 \times {}^0\text{Jan}^{70\text{N}}) \\
 & +(24.2 \times {}^5\text{Jan}^{40\text{N}}) - (287.3 \times {}^0\text{May}^{70\text{S}}) \\
 & +(0.5 \times {}^2\text{May}^{10\text{N}}) + (9.6 \times {}^5\text{Jul}^{80\text{N}}) - 8692.6
 \end{aligned}$$

where ²May¹⁰N, for example, means mid-month insolation in May at 10N, with insolation leading CO₂ concentration by 2 kyr.

This same regression was used here for the next 1 million year (Figure 2). Burgess's regression shows the CO₂ concentration varying between about 180 ppmv and 300 ppmv. This range of variation is similar to that of the Vostok record. However this natural scenario does not exhibit the clear 100 kyr periodicity displayed by the Vostok record, most probably because the regression was based on a 15 kyr long time interval. Rather the future scenario is strongly marked by a precessional signal. Moreover, the Burgess's regression under predicts by about 40 ppmv for the latter part of the Holocene. The reason for this under prediction is unknown, but human influences on patterns of vegetation with the rise of extensive agriculture cannot be ruled out [Ref. 10].

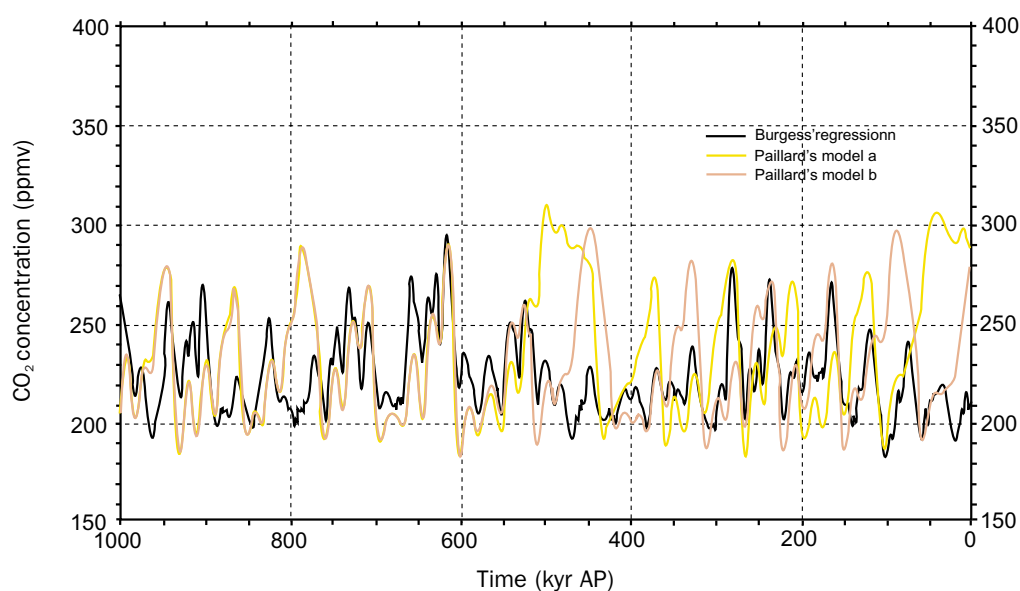


Figure 2: The natural atmospheric CO₂ scenarios from Burgess's regression and from Paillard's model over the next 10³ kyr.

2.2.1 - Threshold model

Another natural CO₂ scenario is computed from the simple threshold model from Paillard, [Ref.11]. Moreover two values for a critical threshold are leading to similar simulated ice volume and CO₂ concentration in the past but different ones in the future. Ice volume and CO₂ concentration are computed simultaneously using this threshold model. Paillard's CO₂ scenarios (Figure 2) have an amplitude similar to, or slightly larger than Burgess's regression. However, their standard deviation is larger than Burgess's. Moreover, the Paillard's scenarios are strongly marked by the 100-kyr period of eccentricity.

The major difference between the a and b scenarios from Paillard occurs over the next 50 kyr and between 400 and 450 kyr AP. For both periods, the low eccentricity favours an extended period of interglacial climate and the CO₂ concentration remains higher than 280 ppmv for more than 50 kyr. In scenario b, the 100 kyr cycles are much more regular, with very short periods of high CO₂. Moreover, the two Paillard's scenarios (a and b) are out of phase from 100 to 400 kyr AP.

2.3. - Combined natural variations and fossil fuel contribution

In order to combine natural variations with the enhancements associated with the burning of fossil fuels, consideration must be given to whether the modulations in projected natural concentrations would also affect the fossil-fuel associated enhancements. If the modulations are due to changes in the strength of carbon emissions, the fossil-fuel associated component should not be modulated. However, if the modulations are due to changes in the degree of effectiveness of sinks, such as biomass or the oceans, in sequestering carbon dioxide from the atmosphere, then similar modulations might be expected in the fossil-fuel associated component. In order to give an indication of the uncertainties involved, the two variant scenarios illustrated in Figure 1 were modified using the two different approaches:

a) **Sum**- A contribution of 280 ppmv was subtracted from the fossil-fuel contribution. These values are then added to the predicted natural contribution (either Burgess's regression model or Paillard's threshold model) (sum scenario).

b) **Scaled**- Each of the values from the fossil-fuel contribution at times after 2000 AD was multiplied by the ratio of the predicted natural value at that time to the predicted natural value at the present-day (scaled scenario).

Results from this analysis are shown in Figure 3 for the low and high scenarios of fossil fuel contribution and applying Burgess's regression. Comparison of the two different approaches indicates that there is no strong distinction between them. Moreover similar results are obtained when combining Paillard's CO₂ scenario with the fossil fuel contribution. Therefore it is proposed that the approach in which natural variations are added to the fossil-fuel component (approach a) should be used.

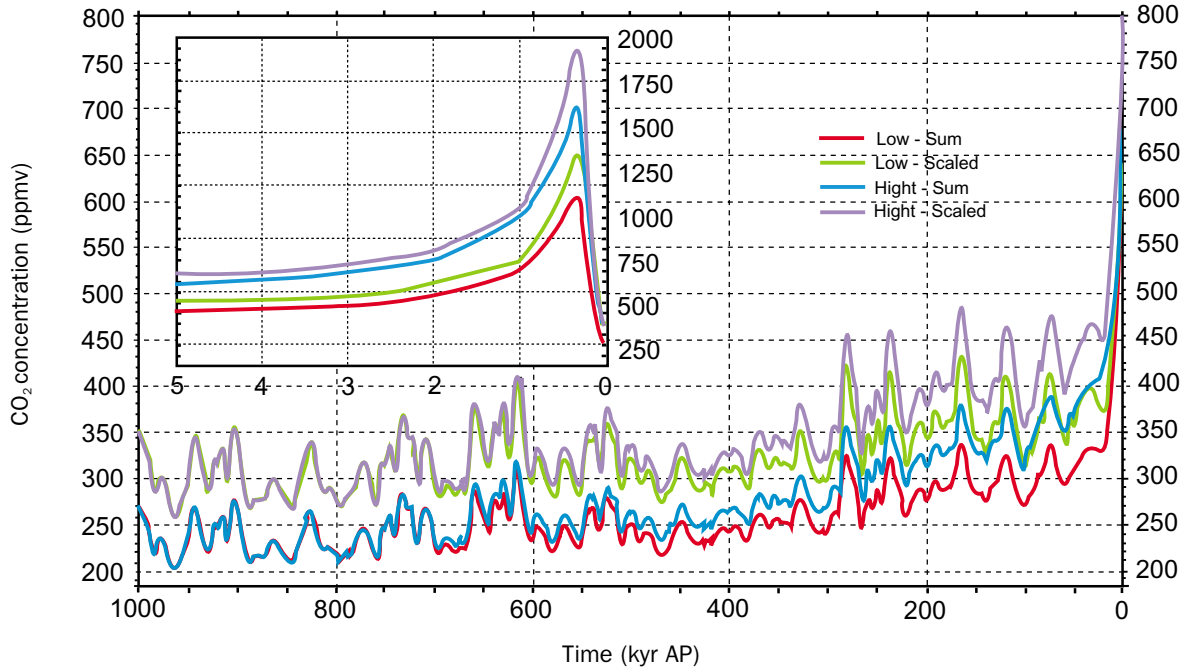


Figure 3: Comparison of different CO₂ scenarios combining (either summing or scaling) the natural atmospheric concentration from Burgess's regression and the fossil fuel contribution either low or high over the next 103 kyr. The inset panel is a blow-up of these scenarios for the next 5 kyr.



3. Climate simulations

3.1. - Description of the simulations

The LLN 2-D NH climate model developed in Louvain-la-Neuve was used to simulate the global climate change over the next 10^6 years (10^3 kyr). This model is forced by the computed latitudinal and seasonal distribution of insolation and by changes in the atmospheric concentration of CO₂. It was started at the present day with the present-day simulated ice sheet (i.e. 3.2×10^6 km³ for the Greenland ice sheet and no other major ice sheet in the Northern Hemisphere). The model is asynchronously coupled with the ice sheet model every 1 kyr except for the next 1000 years when coupling takes place every 25 years (i.e. when the fossil fuel contribution to atmospheric

CO₂ concentration is the largest). The different scenarios of atmospheric CO₂ concentration described above were considered in addition to two constant scenarios, i.e. 210 and 280 ppmv. 280 ppmv corresponds to the pre-industrial atmospheric CO₂ concentration and 210 ppmv is typical of a glacial level. Moreover the continental ice volume simulated with this low CO₂ concentration is showing variations in relatively good agreement with the geological reconstruction for the last few glacial-interglacial cycles, at least as far as the timing is concerned [Ref. 12]. The following table summarises the various CO₂ scenarios.

Table 1: Various scenarios for the atmospheric CO₂ concentration over the next 1000 years. Constant and natural variations can be combined with the fossil fuel contribution either through a sum (+) or scaled according to the ratio of the regression-predicted natural value to the regression-predicted natural value at the present-day ⊕.

CO ₂ scenarios	Constant	Natural variations		Fossil fuel contribution		Combined	
		Burgess's regression	Pallard's threshold model		low		high
			a	b			
A1	280 ppmv				X		+
A2	280 ppmv					X	+
A3		X					
A4a			X				
A4b				X			
A5	210 ppmv						
A6	280 ppmv						
B1		X			X		+
B2		X				X	+
B3			X		X		+
B4			X			X	+
C1		X			X		⊕
C2		X				X	⊕
C3			X	X	X		⊕
C4			X	X		X	⊕

Obviously all the experiments using these various scenarios could not be performed in the time available. In agreement with the recommendations from BIOCLIM participants, it was decided to focus on the scenarios labelled B1, B3 and B4. These allow the study of the impact of the choice of the natural forcing scenario (either Burgess or Paillard) on the simulated climate and the importance of the fossil fuel contribution (either low or high). Some sensitivity experiments were additionally performed to assess the robustness of the

simulated features. This is the reason why it was also proposed to perform simulations A1 and A6 (CO₂ kept constant at 280 ppmv) to test the individual effects of the fossil fuel contribution and the natural CO₂ variations. This A6 simulation could also interestingly be compared with the simulation with low (210 ppmv) CO₂ concentration (A5). On the other hand the role of the natural CO₂ variations (with no fossil fuel contribution) on the simulated climate can be estimated through simulation A3 or A4.

3.2. - The forcings

3.2.1 - Insolation

Most of the time during the next 1Myr (1000 kyr) the insolation varies with large amplitudes (40Wm⁻² at least for mid-month June at 65N; Figure 4). Two periods can be identified that show much smaller amplitude of insolation variability. These

periods (the next 50 kyr and around 400 kyr AP) coincide with periods of small variations in the eccentricity, i.e. minima in the 400-kyr period of the eccentricity change.

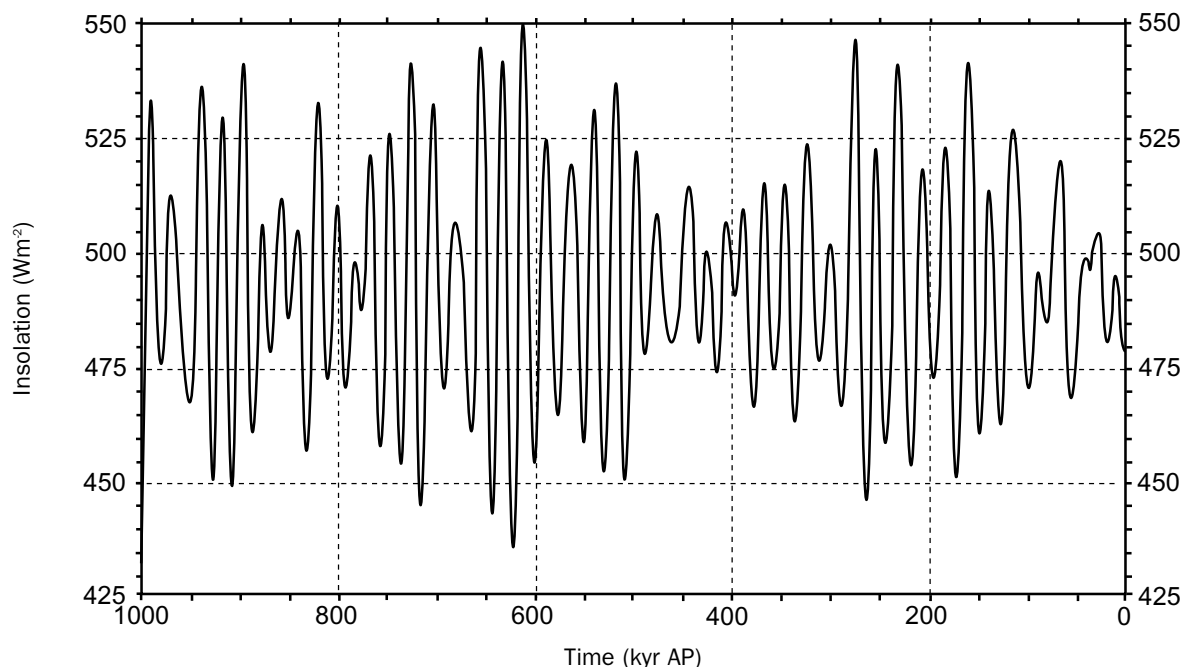


Figure 4: June Solstice insolation at 65N

3.2.1 - CO₂ concentration

The atmospheric CO₂ concentration is used as a second forcing. It has been extensively described in section 2. Figure 5 displays the three

combined scenarios (natural scenario + fossil fuel contribution) used in further experiments.

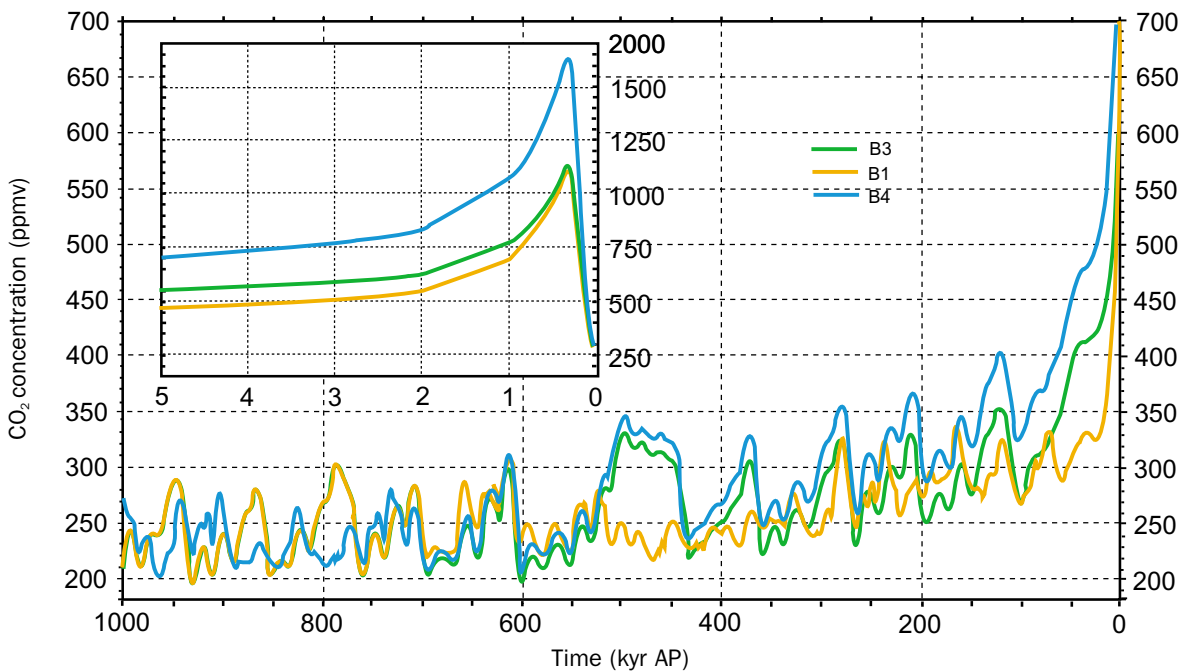


Figure 5: The natural atmospheric CO₂ scenarios from Burgess's regression (B1) and from Paillard's model (B3,B4), are combined (sum) with the fossil fuel contribution (Section 2.1) over the next 10³ kyr. The inset panel is a blow-up of these combined scenarios for the next 5 kyr

3.3. - Results : the simulated climates

Both the LLN 2D NH and the simple threshold climate models are used to simulate future climate.

3.3.1 - Northern Hemisphere continental ice volume

According to the LLN 2D NH model there is hardly any ice sheet during the first half of the simulation with a high constant (280 ppmv) CO₂ concentration (experiment A6; Figure 6). For most of the time, the amount of simulated ice remains less than 3x10⁶ km³ except for three episodes of build-up of ice sheets between 150 kyr AP to 300 kyr AP. Even

then, the amount of ice is still small, i.e. less than 15x10⁶ km³. After 500 kyr AP, the simulated ice volume remains small, although it reaches values larger than 5x10⁶ km³. All the largest ice volumes are associated with very small values of the minimum in June insolation at 65N.

When only natural variations in CO₂ concentration are used, the amplitude of the ice volume change simulated by the LLN 2D NH model can be as large as 37x10⁶ km³. These simulations (A3, A4a and A4b; Figure 7) show that although insolation clearly paces the climate, the CO₂ concentration is able to strengthen or reduce the continental ice volume variation initiated by the insolation change. Consequently, the simulated ice volume becomes rather different in the three simulations. Nevertheless, some robust features can be identified, such as the glacial maxima at around 900 kyr AP and 700 kyr AP, as well as the interglacial periods after 600 and 500 kyr AP. Two intervals of unusual behaviour can be identified, i.e. the next 150 kyr and the interval of time between 300 and 500 kyr AP. First, with

the Burgess's CO₂ scenario (A3), the ice volume remains larger than 20x10⁶ km³ during most of the next 100 kyr, except for a short reversal around 75 kyr AP. Second, the continental ice volume remains larger than 15x10⁶ km³ for more than 150 kyr (from 330 to 490 kyr AP). In contrast, Paillard's scenario A4a leads to very small amount of ice during the next 50 kyr but, similarly to experiment A3, a large amount of continental ice is simulated between 350 and 450 kyr AP. From 300 to 500 kyr AP experiment A4b shows long time intervals of stable ice volume, either glacial (380-440 kyr AP) or interglacial (321-380kyr AP; 440-515 kyr AP). However, these stable periods are much shorter (~60 kyr) than the periods recorded in A3 and A4a.

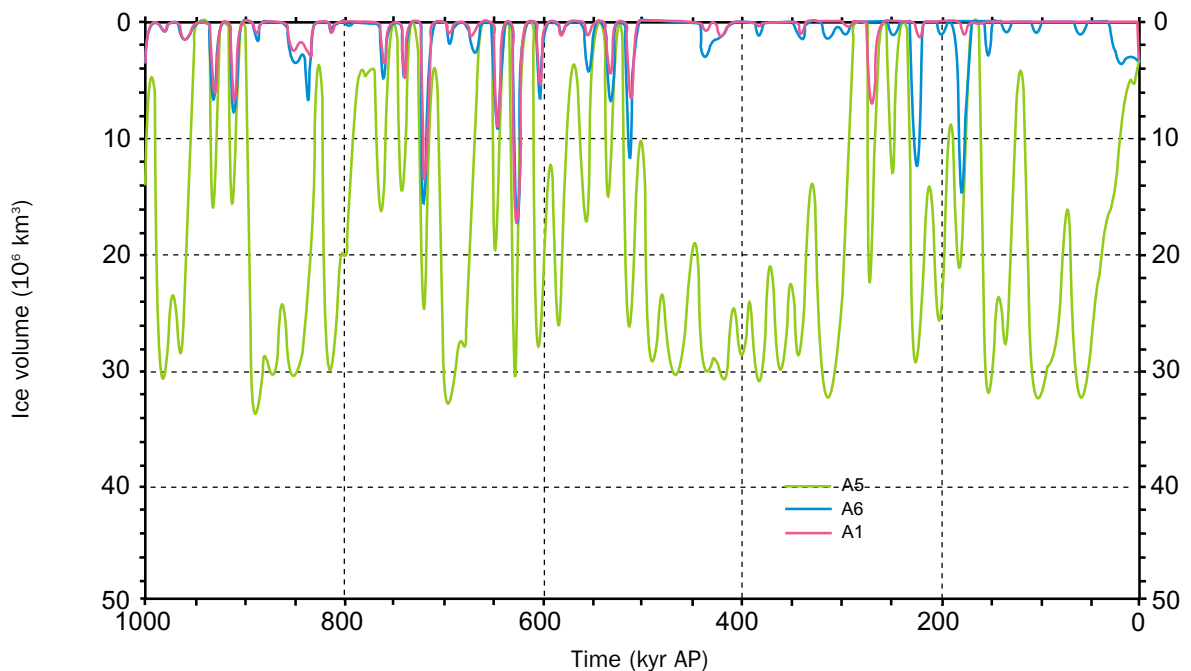


Figure 6: The simulated Northern Hemisphere continental ice volume for experiments A1, A5 and A6.

The results obtained with LLN 2D NH model under nature CO₂ concentration can be compared with those of the simple threshold climate model of Paillard (in Figure 8). When extrapolated over the future, this model produces an exceptionally long interglacial lasting 50 kyr (Paillard_a). However, a slight change in the threshold model (Paillard_b), leads to a completely different result for the next few cycles, where present-

day ice volume is already beyond the glacial inception threshold and consequently the current interglacial becomes as short as the previous one. Moreover, the long glacial identified around 400 kyr AP in A3 and A4a does not appear in Paillard_a or Paillard_b. Instead, there is a long interglacial period simulated from 450 to 550 kyr AP, which corresponds to the very low eccentricity values at that time.

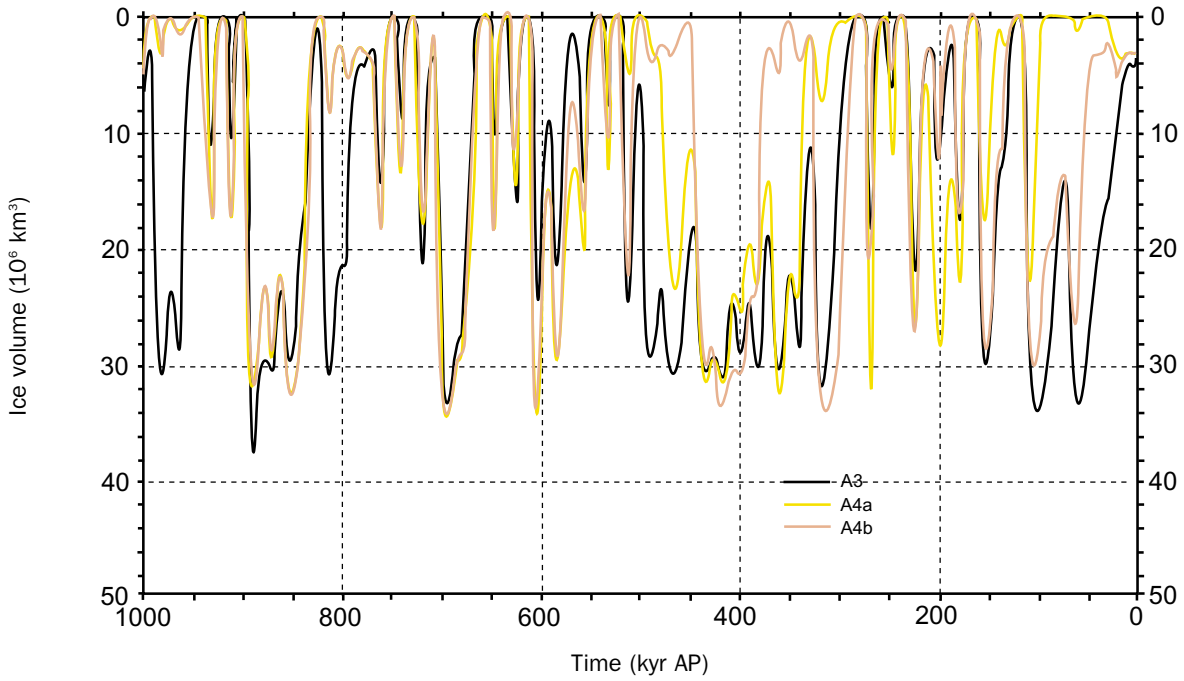


Figure 7: The simulated Northern Hemisphere continental ice volume for experiments A3, A4a and A4b.

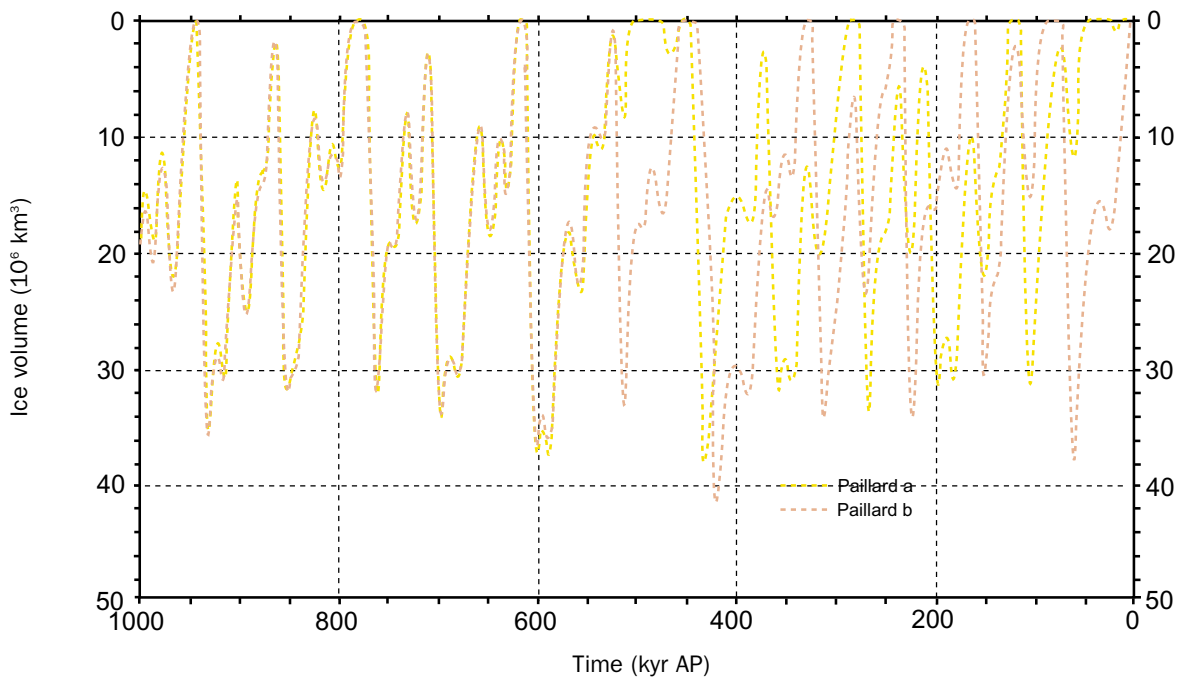


Figure 8: The continental ice volume as simulated by Paillard's threshold models. The amount of ice is scaled with mean and standard deviation similar to LLN 2-D NH simulated ice volume.

The LLN 2D NH model is then used to test the impact of human activities on climate. It has already been shown (Figure 6) that when CO₂ concentration is high the LLN 2D NH model simulates small amounts of continental ice in the Northern Hemisphere, if any (simulation A6). If this CO₂ concentration is heightened because of fossil fuel contribution (simulation A1; Figure 6), the Northern Hemisphere continental ice sheets fully melt over the next 150 kyr and remain smaller than 2x10⁶ km³ for the next 260 kyr. In this simulation, the NH continental ice volume hardly reaches 8x10⁶ km³ except at 625 kyr AP (16.3x10⁶ km³), at 646 kyr AP (8.3x10⁶ km³) and at 719 kyr AP (13.2x10⁶ km³). These periods correspond to strong insolation minima in the summer high latitudes of the Northern Hemisphere.

A last set of simulations (B1, B3 and B4; Figure 9) used combined natural CO₂ concentration (Paillard's scenario a or Burgess's regression) and fossil contribution (scenario low or high). The fossil fuel contribution is largest over the next 400 kyr. Therefore the simulated ice volume remains small (less than 3x10⁶ km³ on average) over most of the next 400 kyr, except for some small cooler excursions at 178, 267 and 361 kyr AP in B3, 224 and 267 kyr AP in B1 and

267 kyr AP in B4. After 500 kyr AP, the fossil fuel contribution becomes smaller and the climate can recover to its natural state. Some differences also appear between the three experiments (B1, B3 and B4). The comparison between B3 and B4 between 300 and 400 kyr AP clearly demonstrates the importance of the 'history' in the simulated climate. The insolation minimum at 344 kyr AP coupled to a low CO₂ concentration (~250 ppmv) leads to the build up of ice sheets. However, the CO₂ concentration is not low enough to sustain the ice sheets during the following warming in simulation B4 and the insolation minimum at 354 kyr AP is not small enough to re-build them. This is not the case in B3. Ice sheets melt only partially from 340 to 343 kyr AP. Then insolation decreases and the ice sheets immediately start to regrow. Between 400 and 450 kyr AP, the continental ice volume is much larger in B1 than in B3 and B4 because the atmospheric CO₂ concentration is much smaller in the B1 scenario. This feature is mainly related to the chosen natural scenario (Burgess's regression shows smaller values than Paillard's model). After 500 kyr AP, the simulations are less and less affected by the fossil fuel contribution to the atmospheric CO₂ concentration. Therefore, the differences between the simulations are similar to those recorded between simulations A3 and A4.

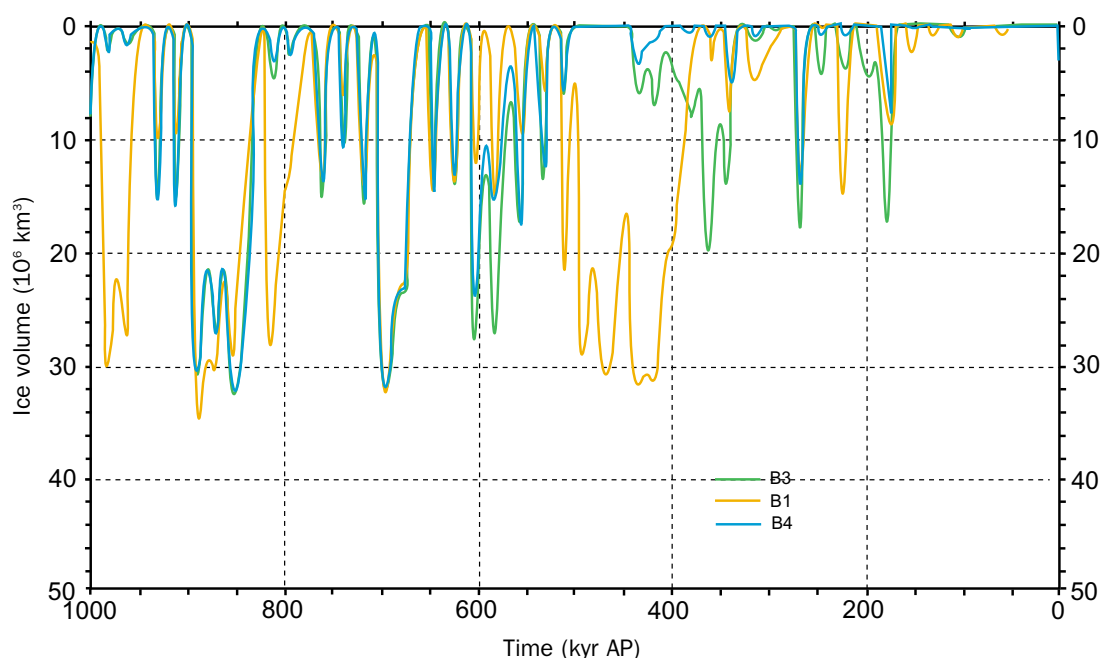


Figure 9: The Northern Hemisphere continental ice volume for simulations B1, B3 and B4.

3.3.2 - Northern Hemisphere annual mean surface temperature

The LLN 2D NH climate model also provides Northern Hemisphere annual mean surface temperature. Under high constant CO₂ concentration (simulation A6) it displays small variation (~2°C) over the next 1 million years. The simulation A5, with lower CO₂ concentration (210 ppmv) leads to slightly larger temperature variations (~2.8°C). The largest amplitudes of changes are obtained when the CO₂ concentration is allowed to vary. For instance, amplitudes reach more than 4°C in simulations A3 and A4. There is a global linear decreasing trend of 2 to 3°C when both natural CO₂ concentration and fossil fuel contribution are taken into account (simulations B1, B3

and B4, Figure 10). This trend is related to the decrease through time of the fossil fuel contribution. Using a high fossil fuel contribution (B4) instead of a low one (B3) leads to a temperature increase of 1.3°C at the maximum. This difference becomes less than 0.5°C after 500 kyr AP. Because of a much lower CO₂ concentration in the Burgess than in the Paillard scenario, the temperature decrease, after the next few centuries of global warming, is much faster in B1 than in B3. All these simulations confirm that the amplitude of the Northern Hemisphere annual mean surface temperature variations is strongly dependent on the atmospheric CO₂ concentration scenario.

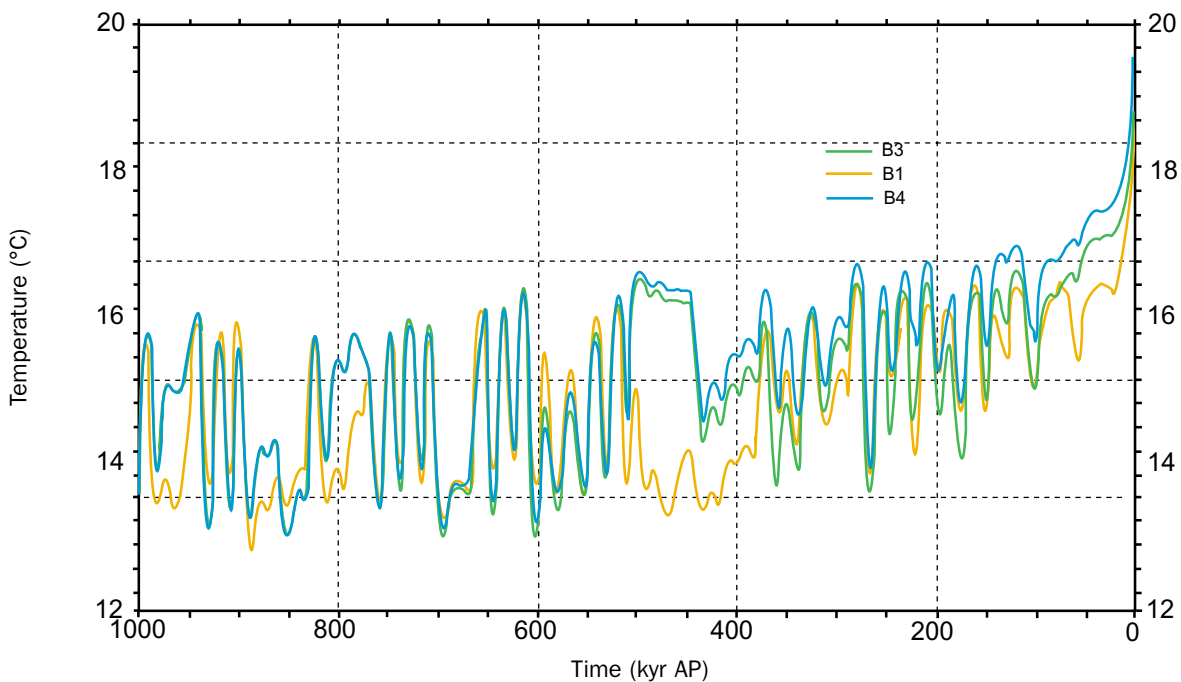


Figure 10: The Northern Hemisphere annual mean surface temperature for simulations B1, B3 and B4

As expected, the larger the CO₂ concentration, the warmer the climate is (Table 2). The simulations forced by the different natural scenarios (A3, A4a and A4b) show very similar features for their amplitudes, as well as mean values and standard deviations. The

difference between them, which can be interpreted as the uncertainties related to the CO₂ natural scenario, is significantly smaller than the temperature increase related to fossil fuel contribution.

Table 2: Mean Northern Hemisphere annual mean surface temperature over the next one million years.

Simulation	A1	A3	A4a	A4b	A5	A6	B1	B3	B4
Mean temperature (°C)	16.0	14.0	14.4	14.3	13.7	15.5	14.8	15.1	15.4

The unusually long glacial time interval identified in the simulated ice volume (simulations A3 and A5) is characterised by low temperature (0.5°C lower on average between 300 and 500 kyr AP than the mean value over the whole interval). However, this feature is less clear in simulation A4a in which the temperature oscillates with an amplitude of 2.3°C in the time interval 300-476 AP. Still this interval can be considered as colder than the average but it can hardly be identified as a strong unusual feature, from the basis of temperature. No long cold time interval can be identified in simulations A1, A4b and A6 although A1 and A6 show less variability during this time than during the rest of the 1 Myr time interval.

The comparison of simulations A5 and A3 or A4 clearly shows that the CO₂ concentration plays an important role in amplifying the temperature response to the insolation as already pointed out by Berger et al [Ref. 13]. For example, the minimum of temperature at 621 kyr AP is 1°C warmer in A3/A4 than in A5. This is related to the larger CO₂ concentration in A3/A4 then. Similarly, low CO₂ concentrations in A3, such as at 100 kyr AP, can be related to lower temperatures in A3 than in A5.



4. Recommendations

Within WP2, the climate modellers were asked to provide scenarios of the atmospheric CO₂ concentration for the next million years, as well as to make suggestions of the time periods for the snapshot experiments to be performed with a GCM. It was suggested that all the GCM time slices to be further studied should be taken, as far as possible, from the same long-term simulation. However, it is not appropriate to stick to a single modelled scenario, since there is a need to account for uncertainties in CO₂ concentrations on the simulated climate, as well as for the uncertainty due to the model itself. Rather, the significance of the orbital parameters in the simulations will be used as guidance for the choice of the time slices, but sensitivity simulations will also be carried out to take account of the CO₂ related uncertainties on the simulated climate. A number of different considerations should be taken into account before the final selection of snapshots is made. The atmospheric CO₂ concentration has varied significantly over the last four glacial-interglacial cycles, as recorded in the Vostok ice core. It has also varied over even longer time intervals. This CO₂ variability can be broadly, but not linearly, correlated with insolation patterns derived from orbital parameters and with estimates of global ice volumes. These natural variations are expected to continue to take place in the future and therefore a scenario for future natural CO₂ variations can be derived from the expected variations in insolation, due to variations in the Earth's precession, obliquity and eccentricity. On this basis, a "natural" CO₂ scenario would provide a robust baseline simulation for investigating the sensitivity of alternative future scenarios.

There is growing evidence that human activities are significantly contributing to increases in the atmospheric CO₂ concentration. Therefore, a scenario taking into account both the natural and fossil fuel contributions seems to be unavoidable. Three such scenarios have been used in the long-term future climate simulations with LLN 2-D NH (Section 3). Although the details of the simulated climates vary, the major features are very similar for all three scenarios. However, the regression approach used is that developed by Burgess [Ref. 10] and it could be

improved. In particular, the statistical relationship between global ice volume, insolation and carbon concentrations could be re-calibrated using the Vostok ice record for the last 400 kyr [Ref. 9]. Nonetheless, the approach of Paillard [Ref. 11], based on a threshold model, is preferred because it involves a more dynamic relationship between insolation, ice volume and CO₂ concentration. Because the differences between the results obtained by adding or by scaling the natural and fossil fuel contributions are small, the simpler way of combining them (summing) is considered acceptable. Moreover, from the high and low scenarios for fossil fuel contributions, the one with the lower cumulative emission of 3160 GtC is preferred, as this is less likely to force the various models to configurations in which glacial-interglacial cycling is completely suppressed. Therefore, scenario B3 is suggested as the most interesting scenario for studying the potential impact of climate and climate change on the biosphere systems of the future (except for a separate sensitivity test with a high CO₂ concentration). There is no a priori reason to prefer one of the two variants of this model. According to Paillard they are equally reliable. Therefore, it was arbitrarily decided to select variant a for scenario B3.

[A number of different selection criteria were suggested to identify the most interesting time slices for further climate studies with a GCM:](#)

- extremely high CO₂ concentration (1600 or 1100 ppmv)
- high CO₂ concentration (550 or 350 ppmv)
- value of CO₂ concentration intermediate between low and high pre-industrial values (250 ppmv)
- low CO₂ concentration (180 ppmv)
- no ice sheet (both Greenland and Antarctic ice sheets completely melted – but see also below for consideration of whether both the West Antarctic and East Antarctic ice sheets should be taken to be completely melted)
- "normal" glacial state
- "normal" interglacial state
- interglacial state due to high CO₂ concentration
- climate state intermediate between "normal" and glacial states

A choice of time slices within the next 200 kyr is preferred, because this is the period of greatest interest to radioactive waste management companies and their regulators. After this period, confidence in assumptions and likely scenarios for a range of geosphere/biosphere factors is likely to greatly diminish. This time interval is unlikely to be equivalent to any time during the Quaternary because of the high CO₂ concentrations induced by human activities. However, it was noted that some simulations relating to 'natural' behaviour (either glacial or interglacial) are already available and could be used in the assessment of future biosphere environments where anthropogenic CO₂ impacts are marginal. Actually, full glacial conditions, such as existed during the Last Glacial Maximum (LGM), and interglacial, the present-day for example, are classical simulations performed using GCMs. Therefore, it is suggested that advantage should be taken of the simulations already performed and to focus on less studied scenarios. It was decided to focus on two major climate states, i.e. glacial and interglacial states. Time slices within transitions (either out of, or into, glaciation or deglaciation) are avoided because they are thought to be too sensitive to the climate history, a parameter that cannot be captured by the GCMs because such models can only represent 'snap-shots' of climatic conditions.

Five scenarios of interglacial states were selected with two different orbital configurations, i.e. present-day and 67 kyr AP. Although the present-day is a full interglacial, the summer insolation received now by the Earth at high northern latitudes is not very large (480 Wm² in June at 65N, i.e. less than the mean value over the last 1 Myr). The insolation at 67 kyr AP corresponds to a moderate maximum in this quantity of 522 Wm² at 65N in June.

A typical CO₂ concentration during past interglacials would be 280 to 300 ppmv. However, already at present and even more in the next millennia, the fossil fuel contribution will augment this natural value. Therefore, three CO₂ concentration values were adopted, i.e. 350 ppmv, 550 ppmv and 1100 ppmv.

The lowest CO₂ concentration scenario corresponds to the present-day value; it is also the value at 67 kyr AP in the B3 scenario. The intermediate CO₂ scenario corresponds to a value that could be maintained up to 67 kyr AP if human activities steadily exhausted all the estimated fossil fuel reserves available globally, leading to a very large human-induced CO₂ contribution. Lastly, the largest CO₂ scenario is close to the 4 x CO₂ simulation used by the IPCC [Ref. 14; Ref. 15].

For global glacial climate state conditions, two ice sheet configurations will be considered, i.e. either with the present-day ice sheet configurations and volumes, or with no ice sheets present in the Northern Hemisphere. Different cases could be considered as far as Antarctica is concerned

- Present-day Antarctica (both West and East Antarctic ice sheets present)
- No West Antarctic ice sheet
- Antarctic ice sheets completely melted

However, the IPCC third assessment reports that temperature would need to rise by more than 20°C to remove the East Antarctic ice sheet. This is considered an unreasonable scenario for present purposes. Such a large change would so modify atmospheric and oceanic conditions, that the validity of current GCMs and AOGCMs could be seriously questioned. Also, as the IPCC has commented in the Technical Summary of the report of Working Party 1, this is a situation that has not occurred for at least 15 million years and a temperature rise of 20°C is far more than predicted by any scenario of climate change currently under consideration.

Table 3 summarises the six scenarios that were selected for further studies with a GCM. [Figure 11](#) indicates the orbital forcing for these scenarios in the context of the next 1 Myr. [Figure 12](#) displays the Northern Hemisphere continental ice volume and annual mean temperature simulated by the B3 scenario under the applicable insolation and CO₂ forcings.

Simulation A is for the very near future, with a very high CO₂ concentration (1100 ppmv). The orbital configuration and the continental ice sheets will be taken to be in their present-day state. This simulation will be carried out for comparison with the present-day baseline simulation (already run as part of the IPCC third assessment). A BIOCLIM simulation is required to ensure consistency in the approach to be carried out for alternative scenarios.

Simulation B. All the simulations performed with the LLN 2-D NH model show that the Greenland ice sheet will disappear in the next few millennia, if a high CO₂ concentration is reached even briefly during the next centuries [Ref. 16]. In this simulation, it is assumed that the CO₂ concentration has already declined to 550 ppmv at the time of complete melting of the Greenland ice sheet. The east Antarctic ice sheet volume is as at present, though its spatial distribution may be somewhat different, with ablation at the margins being compensated for by increased accumulation on the high altitude plateau, but the west Antarctic ice sheet has collapsed. The orbital parameters will be taken at their present-day value. This simulation is required in order to investigate the effects of high CO₂ concentrations, but a reduced global ice volume, on climate change in the near future.

Simulations C, D, E. The simulations performed with the LLN 2-D NH climate model show that, due to the high CO₂ concentration reached in the near future, no large glaciation is expected before 170 kyr. In other words, the climate system is likely to remain in an extended interglacial state for more than 170 kyr. However, during that time interval insolation is oscillating (although less than during the Eemian time) between low and high. At 67 kyr AP, insolation is experiencing a moderate maximum at 65N in June. Simultaneously, the CO₂ concentration will still be high, 338 ppmv in the B3 scenario. At that time, the ice sheets will not have recovered after a postulated collapse. The combined effect of increased insolation (relative to present day), high CO₂ concentration and no ice sheets makes this interglacial scenario very special

(a kind of super-interglacial) at a time of direct relevance to deep repository post-closure safety assessments. Two experiments will be performed for this super-interglacial, with a CO₂ concentration of either 350 ppmv or 550 ppmv. Moreover, in order to test the impact of the ice sheets during such a super-interglacial, a third experiment will be performed with a CO₂ concentration of 350 ppmv and the present-day extension and volume of the continental ice sheets.

GCM experiments have already been performed for the last interglacial (126 kyr BP) [Ref. 17]. The difference in insolation between this time and 67 kyr AP can largely be explained by the change in eccentricity, which is much larger at 126 kyr BP (0.039710) than at 67 kyr AP (0.014271). The largest differences in insolation occur in summer and winter. The amplitude of the seasonal cycle is smaller at 67 kyr AP than at 126 kyr BP. The obliquity at 67 kyr AP (24.138) is close to its value at 126 kyr BP (23.928). Perihelion occurs in the Northern Hemisphere summer at both times.

Moreover, comparison of this already completed simulation with the simulations proposed here will also allow for some sensitivity analyses in order to study the impact on both climate and vegetation distribution of:

- the CO₂ concentration (on either the present-day climate or the climate at 67 kyr AP))
- the orbital configuration
- the ice sheets at 67 kyr AP, for post-industrial CO₂ concentrations

Simulation F. For the glacial state, the focus will be on the first episode of widespread glaciation occurring in the B3 simulation at 178 kyr AP (Table 3). The continental ice volume is maximum at 178 kyr AP although the minimum of CO₂ concentration is reached at 171 kyr AP with a rather low value of 263 ppmv and the minimum of summer insolation is at 175 kyr AP (455 Wm² in June at 65N). This time difference accounts for the time lag between forcing and climate response, in particular ice sheet build-up.

At 175 kyr AP the Northern Hemisphere continental ice volume is then $17.4 \cdot 10^6 \text{ km}^3$, which is much less than during the LGM, but substantially more than at present, with substantial amounts of ice present in both North America and Eurasia. The atmospheric CO_2 concentration is 275 ppmv in the B3 scenario. This is a pre-industrial value, which means that CO_2 concentration will already have recovered from the high CO_2 concentration resulting from fossil fuel contributions.

In addition to the six BIOCLIM scenarios, the results from three existing simulations will also be used; i.e. present-day climate as the baseline for the interglacial experiments, LGM climate as the baseline for full

glacial conditions, and the simulated climate at 126 kyr BP as a 'pronounced' interglacial state.

Within this programme and because of high computer costs and computer time, as well as limited manpower, this study is restricted to six GCM simulations. Nevertheless we are aware that other time slices are as interesting as those selected here. For example, in a provisional shortlist full glacial, full interglacial and transitional states under natural CO_2 concentrations only (i.e. after 500 kyr AP) were suggested. Another suggestion was to study an interglacial resulting from high CO_2 concentration, in other words an interglacial that would have been a glacial under natural CO_2 concentration

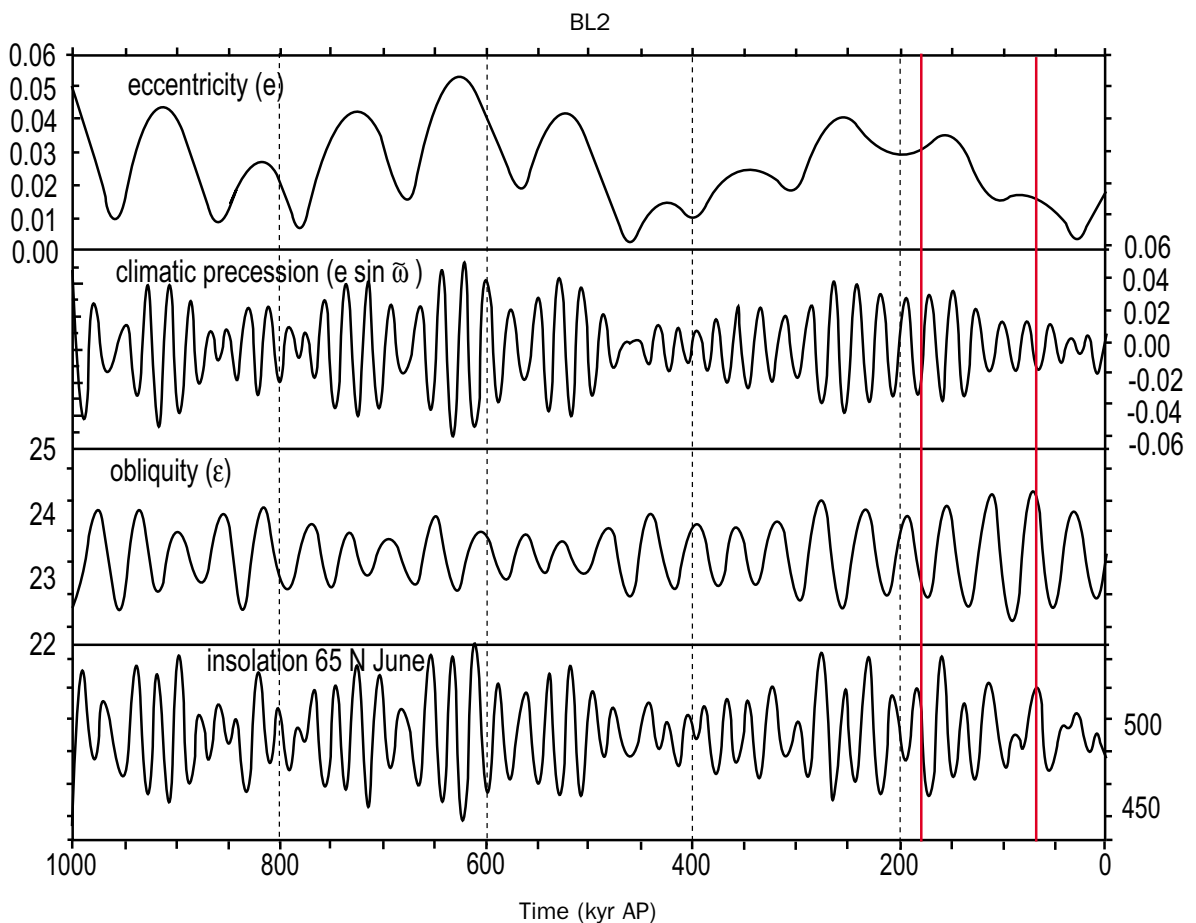


Figure 11: The orbital parameters and insolation at 65°N in June. The red lines indicate the three selected time slices for GCM simulations.

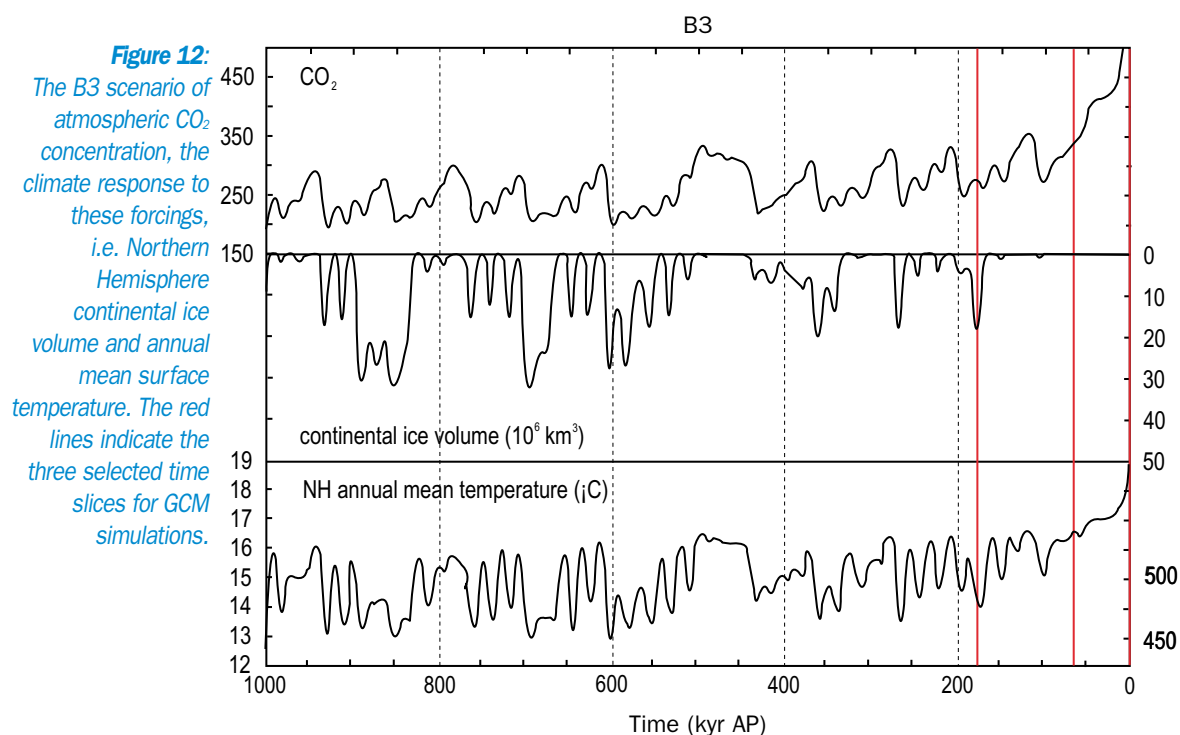


Table 3: Some characteristics of the time slices for GCM simulations. The table gives the orbital parameters and the insolation (mid-month value at 65N in June), and the Northern Hemisphere continental ice volume simulated by B3. The simulations in **bold** will not be performed within the framework of this project. Rather results available elsewhere will be used. Note: PRS means present time

Priority	Name	Time (kyr)	Eccentricity	Longitude perihelion (deg.)	Obliquity (deg.)	Insolation (Wm ²)	CO ₂ (ppmv)	Ice sheets	Ice volume (10 ⁶ km ³)
Baseline	PRS	0,016724	102,04	23,446	480	345	As present	3,2	
5	A	PRS	0,016724	102,04	23,446	480	1100	Y	3,2
4	B	PRS	0,016724	102,04	23,446	480	550	N	
6	C	67	0,014271	295	24,138	522	550	N	
2	D	67	0,014271	295	24,138	522	350	N	
1	E	67	0,014271	295	24,138	522	350	Y	3,2
Last interglacial		126 kyr BP	0,039710	291,24	23,928	544	280	As present	3,2
Baseline - LGM		21 kyr BP	0,018994	114,42	22,949	472	200	Peltier	
3	F	178	0,029860	217	22,858	505	275	Y	17,4
Glacial inception		115 kyr BP	0,041421	110,88	22,404	444	280	As present	3,2



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