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Clues from MIS 11 to predict the future climate – a modelling point of view

M.F. Loutre *

Institut d'astronomie et de géophysique Georges Lemaître, Université catholique de Louvain, 2, Chemin du Cyclotron,
B-1348 Louvain-la-Neuve, Belgium

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Abstract

Simulations performed with the LLN two-dimensional Northern Hemisphere climate model have confirmed that climate is largely triggered by changes in insolation forcing although atmospheric CO_2 concentration also plays an important role, in particular in the amplitude of the simulated variations. Marine isotope stage 11 (MIS 11) some 400 kyr ago and the future share a common feature related to climate forcing, i.e. the insolation at these times displays small similar variations. MIS 11 can be considered an analogue for future natural climate changes. Different simulations were performed to identify the conditions constraining the length of the MIS 11 simulated interglacial. Clearly its length strongly depends on the phase relationship between insolation and CO_2 variations. It is only when insolation and CO_2 act together towards a cooling, i.e. they both decrease together, that the climate enters quickly into glaciation and that the interglacial may be short. Otherwise each forcing alone is not able to drive the system into glaciation and the climate remains in an interglacial state. The same situation applies for the future. However, we already know that CO_2 and insolation do not *play together*. Indeed, insolation has been decreasing since 11 kyr BP and CO_2 concentration remains above 260 ppmv, with a general increasing trend over the last 8000 yr. Therefore we conclude that the long interglacial simulated for the future is a robust feature and the Earth will not enter naturally into glaciation before 50 kyr AP.

Keywords: Marine isotope stage 11; Future climate; Palaeoclimate modelling; EMIC

1. Introduction

Early attempts to predict future climate suggested that the next glacial maximum was imminent [1]. Indeed, the last two interglacials were believed to have lasted about 10 kyr, which is about the length of the Holocene. Further studies, based on statistical rules or simple models, predicted a cold interval in about 25 kyr and the next glaciation in 55 kyr [2,3]. However, these studies did not take into account the CO_2 forcing. Others [4,5] disagreed with these projections, suggesting that the next glacial maximum would not take place before 65 kyr AP, at the earliest. From the standpoint of insolation, the most recent past analogue for the next millennia [6] occurred at about 400 kyr BP, during marine isotope stage

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* Tel.: +32-10-473299; Fax: +32-10-474722.
E-mail address: loutre@astr.ucl.ac.be (M.F. Loutre).

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(MIS) 11. Therefore the climate behaviour during MIS 11 can help us to understand what the future climate could be.

Based on a series of cores from the South Atlantic sector of the Southern Ocean, Hodell et al. [7] show that surface water temperatures during MIS 11 were not significantly warmer than during other interglacial stages at high southern latitudes, although the period of warmth lasted longer, at least twice as long as the other interglacial stages. Similar results were obtained for the Southwest Pacific Ocean [8]. The warm MIS 11 was estimated to last for 25–30 kyr from microfossil and isotopic data from marine sediments of the Cariaco Basin [9]. Consistently, the North Atlantic is experiencing the longest relatively ice-free interval as well as the longest interval (30–40 kyr) without amplified millennial-scale sea surface temperature variability [10]. The absence of ice-rafted debris for about 23 kyr during MIS 11 in the North Atlantic [11] suggests full interglacial conditions with small continental ice volume in the Northern Hemisphere [12]. In contrast, several terrestrial continental records, e.g. pollen record from Europe, Asia, Australia, New Zealand and America [13], indicate that MIS 11 temperature was warmer than during the Holocene and MIS 5, or at least as high. MIS 11 is also the warmest period in Brunhes chron recorded in Lake Baikal [14]. The loess sequences in Northern China [15] show evidence that the summer monsoon during MIS 11 was particularly strengthened, which is typical of warmer climate. Sea-level highstands at about +20 m, dated at about MIS 11, were identified in northern Alaska [16], in England [17], in Bermuda and the Bahamas [18,19] and in the Cariaco Basin [9]. MIS 11 is also characterised by unusual carbonate plankton blooms in high latitudes [20], massive coral reef build-up [21] and overall poor pelagic carbonate preservation [22,23].

The Vostok ice core gives a continuous climate record back to MIS 11, which provides us with climatic information complementary to marine and continental records [24]. In particular, it provides a unique record of greenhouse gases back to 414 kyr BP. However, it is still unclear whether the oldest section of the undisturbed part of the Vostok core recorded the optimum of the climatic interglacial [25]. It is hoped that potential sites in Antarctica, such as Dome Concordia, may deliver undisturbed records going back to MIS 12 and further.

Several attempts have been made to reconstruct the time evolution of the changes in the global continental ice volume or in the related sea-level change (Fig. 1). Imbrie et al. [26] built a composite record based on the variations in five $\delta^{18}O$ records obtained from pelagic foraminifera at open-ocean sites in low and middle latitudes. The time scale of this record (SPECMAP time scale) is obtained from its correlation with the obliquity and precession signals. Alternatively the stacked $\delta^{18}O$ record of core MD900963 and ODP site 677 [23] can also be used as a reference record for low-latitude Upper Pleistocene $\delta^{18}O$. Recently, Shackleton [27] attempted to separate the $\delta^{18}O$ signals of ice volume, deep-water temperature and a varying Dole effect from the benthic marine $\delta^{18}O$ record V19-30 using the record of $\delta^{18}O$ in atmospheric oxygen trapped in Antarctic ice at Vostok.

Simulations performed with the LLN two-dimensional Northern Hemisphere (2-D NH) climate model already suggested that MIS 11 could have lasted longer than the later interglacial stages [28,29]. In a first step these previous experiments will be briefly reviewed. They highlight the importance of the phase relationship between insolation and CO_2 forcings for the length of the interglacial [25,28] (Section 3.3). In a second step (Section 3.4), in the light of the simulated climate during MIS 11, we will discuss the robustness of the simulated climate over the next 130 kyr. All these experiments take into account the natural variation of the CO_2 concentration and not the additional input related to the human activities.

2. Climate forcings

2.1. The insolation forcing

Insolation changes at the top of the atmosphere are computed from three orbital parameters, i.e. the eccentricity (e), the obliquity (ε), and the cli-

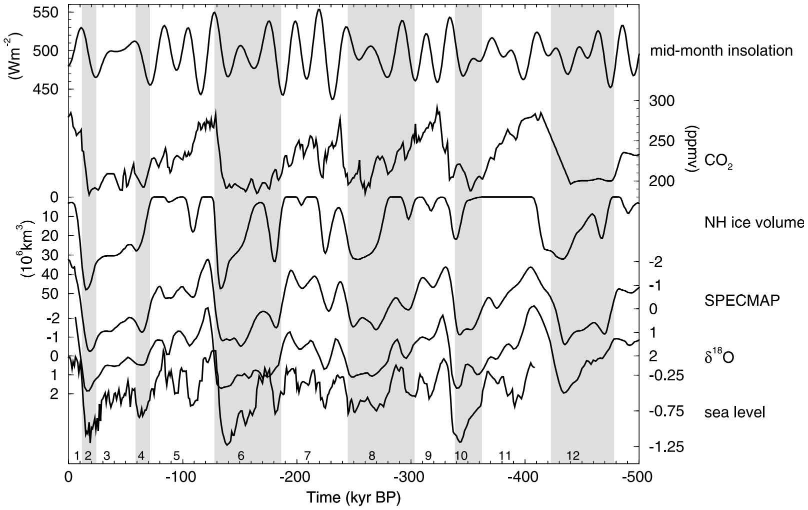

Fig. 1. Variations over the last 500 kyr of (from top to bottom): the mid-month insolation (W m^{-2}) at 65°N in June [30], the atmospheric CO_2 concentration (ppmv) (from [24] after 414 kyr BP and from [37] prior to 414 kyr BP (see text)), the simulated Northern Hemisphere continental ice volume (10^6 km^3) (reference simulation, see text), the stacked, smoothed oxygen isotope record as a function of age in the SPECMAP timescale [26], the stacked $\delta^{18}O$ record of core MD900963 and ODP site 677 [23] and the sea level (scaled as O^{18}) [27]. The SPECMAP time scale [26] is used for the stage boundaries.

matic precession ($e\sin\varpi$) [30]. The climate responds to the insolation forcing at all latitudes and times in the year, although 65°N June is often taken as a guideline for the analysis. Insolation at all latitudes and times in the year, except high latitudes in wintertime, is strongly imprinted by precession. During MIS 11 the eccentricity is very small. Climatic precession is modulated in amplitude by eccentricity. Therefore, the amplitude of variations of precession, as well as of insolation, is small. For example, between 423 and 362 kyr BP (MIS 11 according to SPECMAP time scale [26]; the stage boundaries are defined by Shackleton and Opdycke [31]) the amplitude of the insolation change at 65°N in June is ~60 W m^{-2} while it is more than 107 W m^{-2} during MIS 5 and it reaches 116 W m^{-2} over the last 500 kyr (Fig. 1).

The major feature of the insolation over the next 130 kyr is also the small amplitude of its variations (Fig. 2). For example, the amplitude of the long-term variations of the mid-month insolation at 65°N in June remains lower than 30 W m^{-2} from 0 to 50 kyr AP and barely reaches 65 W m^{-2} at the end of the 130-kyr interval). This strong similarity between MIS 11 and the future must be related to the minimum in the 400-kyr cycle of the eccentricity at around 370 kyr BP and 30 kyr AP.

2.2. The CO_2 forcing

The extended Vostok ice core record [24] pro-

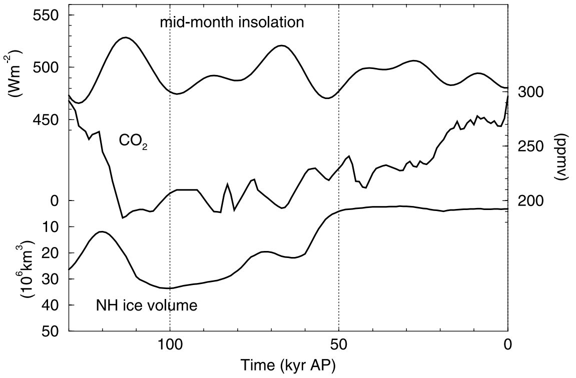

Fig. 2. Variations over the future of (from top to bottom): the mid-month insolation (W m^{-2}) at 65°N in June [30], the atmospheric CO_2 concentration (ppmv) (Vostok CO_2 values [58] shifted by 131 kyr towards the future) and the simulated Northern Hemisphere continental ice volume (10^6 km^3) (reference simulation, see text).

vides an undisturbed picture of the atmospheric changes over the last four climatic cycles, back to the MIS 11 period (Fig. 1). The current chronology is based on a glaciological time scale established by combining ice flow and an accumulation model. This glaciological time scale (GT4) provides a chronology based on physics, without assumptions about climate forcing except for two control points, i.e. MIS 5.4 (110 kyr BP) and MIS 11.2 (390 kyr BP). The accuracy of the time scale was estimated to be better than 15 kyr. During the glacial–interglacial transitions, atmospheric CO_2 concentration rises from 180 to 280–300 ppmv. The CO_2 decrease from interglacial to glacial times is slower than its increase towards interglacial values. The 100-kyr component dominates the CO_2 records [32]. During MIS 11, the CO_2 concentration remains above 275 ppmv from 414 kyr BP (the beginning of the record) to 397 kyr BP. Then it decreases regularly (around 1.9 ppmv/kyr) until the minimum value of 188 ppmv is reached at 352 kyr BP. There is one brief reversal of 13 ppmv from 392 to 385 kyr BP. On the other hand, the most recent part of the record shows an increase of the CO_2 concentration starting at 18 kyr BP. It reaches values higher than 275 ppmv for the last 3000 years.

The atmospheric CO_2 concentration is, in some complicated ways, related to climate. Indeed, any climatic change, such as surface temperature or precipitation change, will impact the carbon cycle. For example, marine productivity and terrestrial vegetation can be affected, the amount of carbon stored in the ocean and in the soil can be modified, the weathering of terrestrial rocks and the burial of biogenic particles into the seafloor sediments can be altered. Moreover, the exchange of carbon between the different reservoirs (atmosphere, ocean, soil and land biota) can also be greatly affected. All these potential changes in the carbon cycle will modify the greenhouse gas balance in the atmosphere. In turn, such a modification will feedback on the climate. Ideally a carbon cycle coupled to the LLN 2-D NH climate model would be required to simulate future climate changes. In the absence of such a coupling, different scenarios for CO_2 concentration were used as a first approximation to the future CO_2 changes (Section 3.4).

3. Climate simulation

3.1. The general purpose

The LLN 2-D NH climate model was specially designed to simulate and study long-term climate variations in response to Milankovitch forcing. It is a model of intermediate complexity [33], which links the atmosphere, the upper mixed layer of the ocean, the sea ice, the continents, the ice sheets and their underlying lithosphere. It considers only the Northern Hemisphere [34]. Climate simulations performed with this model have already shown its ability to reproduce the glacial–interglacial cycles, similar to those reconstructed from proxy data. Although far from being comprehensive, this model has been able to represent several gross features of the climate of the last 3 million years: the entrance into glaciation around 2.75 Myr BP [35], the late Pliocene–early Pleistocene obliquity cycle [36], the emergence of the 100-kyr cycle around 900 kyr BP [36], the glacial–interglacial cycles of the last 600 kyr [37], the climatic variations over the last 200 kyr [6]. A major weakness of the model still lies in the too-frequent melting of the Northern Hemisphere ice sheets, including the Greenland ice sheet, during the interglacials but this does not prevent it from simulating the timing of the glacial–interglacial cycles. The discussion will be based on the simulated continental ice although the model also simulates other variables.

As MIS 11 can be considered a good analogue for our future climate or more precisely for what the natural future climate would be [38], the simulations of both MIS 11 climate and the future climate performed with the LLN 2-D NH model will be compared to identify the strong and weak points of the simulation for the future.

3.2. The reference simulations

The reference simulation for MIS 11 (Fig. 1) is performed using both variable insolation [30] and atmospheric CO_2 concentration from the Vostok ice core [24]. The CO_2 record is extended prior to 414 kyr BP using the statistical scenario of CO_2 variations from Li et al. [37] as described in Raynaud et al. [25]. The purpose here is to focus on MIS 11, some 400 kyr BP. Therefore Li et al.'s scenario of CO_2 variations for time prior to the Vostok record is only used to provide the model with initial conditions at the beginning of MIS 11. With this experimental set-up, the model simulated an exceptionally long ice-free period of 45 kyr during MIS 11. Moreover, the continental ice volume remains lower than 10×10^6 km^3 over 65 kyr [25].

The simulated ice volume over the last four glacial–interglacial cycles compares very well with the reconstruction of past sea-level changes obtained from oxygen isotope record of marine cores [23,26,27] (Fig. 1). In particular, the timing for the glacial and interglacial times is especially well reproduced.

As for MIS 11, the future climate is simulated using both insolation [30] and CO_2 concentration (Fig. 2) as forcings. The model predicts a long-lasting interglacial (~50 kyr), characterised by a small amount of continental ice in the Northern Hemisphere (Fig. 2) [39], similar to the present-day value. Except for a brief reversal, the continental ice volume increases steadily from 50 kyr AP towards the glacial maximum, reached shortly after 100 kyr AP.

MIS 11 and the future not only undergo a similar astronomical forcing characterised by small amplitude of its variations but also the simulated climates during these stages are similar. Indeed, during both interglacials very small Northern Hemisphere continental ice sheets, if any, are simulated over more than 40 kyr. This makes MIS 11 and the future unusually long interglacials [29,39].

However, some uncertainties remain over the MIS 11 simulated climate. The Vostok ice chronology (GT4) [24] was said to be uncertain by about 15 kyr. The initial conditions at 414 kyr BP and/or the CO_2 scenario prior to 414 kyr BP are not known. Therefore sensitivity tests were performed to test the robustness of this long-lasting MIS 11 interglacial in our model and to identify the conditions that constrain its simulated length. The insight gained into the climate behaviour during MIS 11 will then be applied for the future climate.

3.3. Sensitivity experiments on MIS 11 climate

In contrast to more recent interglacial stages the LLN 2-D NH climate model is not able to reproduce the MIS 11 interglacial when forced by computed insolation and a low constant CO_2 concentration (210 ppmv) [40]. As pointed out by Li et al. [37], this inability of the model suggests that the direct insolation forcing alone, i.e. without its effects on the carbon cycle, is not sufficient to explain the warm climate during MIS 11, or at least that the CO_2 concentration must reach a higher level to allow MIS 11 to become an interglacial. On the other hand, Loutre and Berger [41] showed that the long-term atmospheric CO_2 variations alone are not able to drive the climate system into any glacial–interglacial cycles for the ice volume.

Two strategies can be used to start off the simulation. Either the simulation is started well before the beginning of the CO_2 record and a CO_2 scenario (either constant or not) is prescribed before 414 kyr BP so that the model would forget the initial conditions at MIS 11, or the simulation is started at the time of the beginning of the CO_2 record (414 kyr BP) and some initial boundary conditions (i.e. the ice sheets) are assumed.

Using the first strategy, different simulations starting at 575 kyr BP [25] exhibit a very long MIS 11 interglacial without continental ice in the Northern Hemisphere from 405 kyr BP to 362 kyr BP. Some significant differences between the simulations arise prior to 414 kyr BP but are not relevant for the present study.

Results already published [25] show that different initial ice sheet configurations at 414 kyr BP, in agreement with MIS 11 being an interglacial, lead to a long interglacial (more than 50 kyr) with no ice or very small ice sheets in the Northern Hemisphere.

Previous experiments already underlined the importance of CO_2 concentration when insolation changes are small [42]. Therefore different scenarios were tested during MIS 11. The MIS 11 CO_2

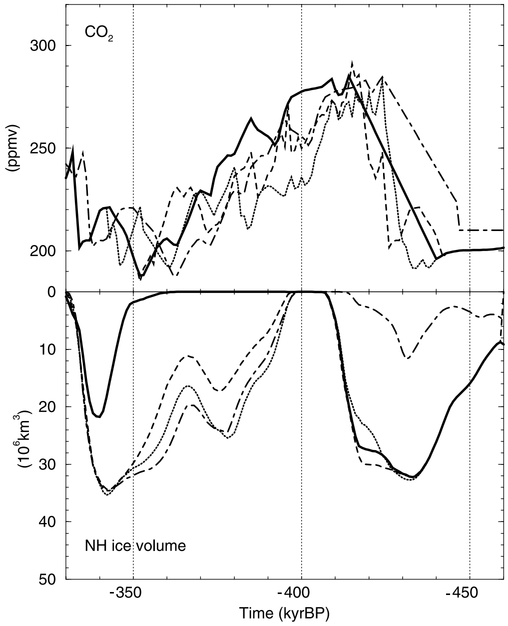

Fig. 3. CO$_2$ forcing (top) and response of the model (Northern Hemisphere continental ice volume, bottom) over stages 12–10. Different CO$_2$ scenarios are used during MIS 11. The reference simulation is indicated by the solid line. The CO$_2$ concentration from 438 to 343 kyr BP (MIS 11) is replaced by that between 143 and 48 kyr BP (MIS 5) (dotted line). The CO$_2$ concentration during MIS 11 (442; 352 kyr BP) is replaced by that of MIS 9 (350; 260) (dashed line). The MIS 11 CO$_2$ series is made older by 10 kyr (dash-dotted line).

concentration is replaced by either the MIS 5 or the MIS 9 CO$_2$ concentration [25]. The model then simulates a short interglacial followed by a very fast glaciation towards the glacial maximum briefly interrupted by a short reversal (Fig. 3). These experiments suggest a significant impact of the CO$_2$ concentration on the length of the interglacial MIS 11. This was confirmed by another test for which the MIS 11 CO$_2$ series is made older by 10 kyr (Fig. 3). These experiments lead us to hypothesise that a slightly modified chronology of the CO$_2$ record during MIS 11 could lead to simulation of a short interglacial followed by a rapid glaciation. It was suggested that the timing of the CO$_2$ decrease after the peak interglacial is the key point for the length of the interglacial itself [25]. Moreover, regarding the uncertainty on the GT4 chronology such a change remains reasonable.

Finally, other chronologies than GT4 were applied on the Vostok CO$_2$ record. Shackleton [27] generated a new time scale for the Vostok ice core (air) by tuning the $\delta^{18}O_{atm}$ record to a synthetic signal made of obliquity and precession. The age of the mid-point of the most recent glacial-to-interglacial transition (i.e. 12 kyr BP) is selected as independent age to determine the phase of the record relative to precession. The same chronology is then used for the CO$_2$ record (which is measured in the same samples) (Fig. 4). Large differences between this chronology and the GT4 one arise during MIS 11 and the decrease of CO$_2$ towards MIS 10 glacial values. The CO$_2$ value of 247 ppmv reached at 380 kyr BP in the GT4 chronology was already reached 5 kyr earlier in Shackleton's chronology although the lag between the chronologies was only 1 kyr at 392 kyr BP. However, Fig. 4 shows that these changes in the chronologies do not significantly affect the simulated ice volume over the Northern Hemisphere.

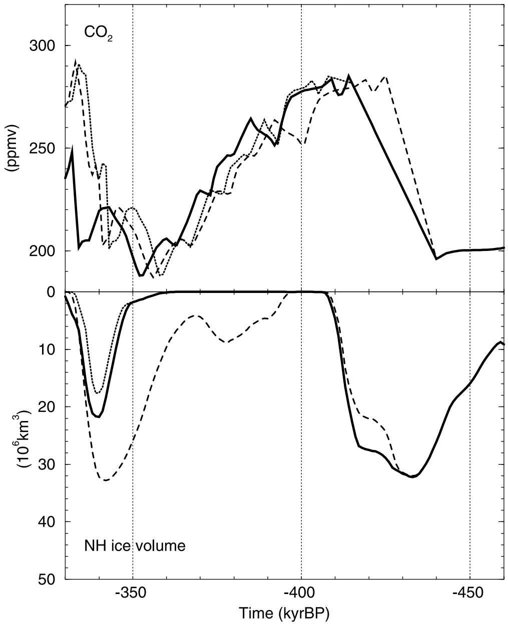

Fig. 4. CO$_2$ forcing (top) and response of the model (Northern Hemisphere continental ice volume, bottom) over stages 12–10. Different time scales for the CO$_2$ series are used during MIS 11. GT4 [24] (reference simulation, solid line), Shackleton [27] time scale (dotted line) and an arbitrarily tuned time scale (dashed line).

This experiment must also be compared with another one, in which the time scale of the CO_2 concentration changes during MIS 11 and 10 was arbitrarily modified (Fig. 4). Then the model simulated a short period ($\sim$12 kyr) with no ice in the Northern Hemisphere. However, the interglacial interval remains rather long if we consider, for example, the time interval during which continental ice volume is smaller than 10×10^6 km^3 (53, 36, 35 kyr for MIS 11, 9, 7 respectively).

All these experiments on MIS 11 let us conclude that the time scale of the CO_2 concentration decrease plays a major role for the simulation of a short interglacial during MIS 11. In particular, if CO_2 concentration decreases simultaneously with the insolation decrease, the climate enters earlier into glaciation while, if CO_2 concentration remains high when insolation decreases, i.e. insolation and CO_2 play opposite roles, the climate remains in its interglacial state with no ice.

Fig. 5 summarises these results and others not shown here. The continental ice volume simulated at 390 kyr BP, i.e. 21 kyr after the summer insolation maximum, is represented as a function of the lag between insolation and CO_2 concentration. This lag is computed as the time interval elapsed between the insolation maximum (411 kyr BP) and the time at which CO_2 concentration becomes lower than 260 ppmv. This figure clearly shows that only a very short range of time lags (5–9 kyr) allows a significant ice sheet to be built at 390 kyr BP.

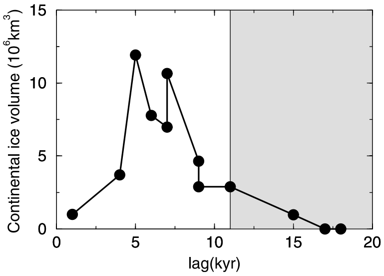

Fig. 5. Relationship between time lag between insolation and CO_2 concentration, and the following glacial inception (see text for details). This figure is based on several experiments performed over MIS 11. The hatched part of the figure corresponds to the part of this phase diagram available for the future.

3.4. Robustness of the simulated future climate

As MIS 11 could be a good analogue for our future natural climate, i.e. for what our climate would be without the impact of human activities [6,38], we can apply the conclusion drawn about the length of the MIS 11 interglacial to our future climate. In particular, because of the small amplitude of the insolation changes, climate can only enter into glaciation after the interglacial if both insolation and CO_2 concentration decrease. For the Holocene and the future, we are in a very favourable position to predict climate. Indeed, the insolation already started to decrease some 11 000 years ago. However, the CO_2 concentration over the last 11 kyr remains high (close to 260 ppmv). This situation is similar to what happens in the reference simulation for MIS 11 (GT4 time scale). Contrarily to MIS 11, there is absolutely no uncertainty on the forcing over the last 11 kyr. Our present interglacial can be put in Fig. 5, assuming that the same processes are working now as during MIS 11. The lag between insolation and CO_2 concentration already reaches a value larger than 10 kyr now. Therefore the continental ice volume in 10 kyr would be lower than or equal to the present-day value. Moreover, MIS 11 experiments demonstrate that, in such a case, glacial inception is further delayed. Consequently, the next glacial inception should not start within the next 40 kyr.

In order to confirm this conclusion, different experiments were performed over the next 130 kyr using insolation changes [30] and different CO_2 scenarios (Table 1 and Fig. 6). Except for scenario A, all the simulations predict a long-lasting interglacial, characterised by a small amount of continental ice in the Northern Hemisphere (Fig. 6) [29]. In scenario D, the Northern Hemisphere continental ice sheets melt completely at 30 kyr AP, and large ice sheets do not reappear before 100 kyr AP. This contrasts with simulations B, C and E where some continental ice remains until 50 kyr AP, when re-growth of the ice sheets takes place. After 60 kyr AP, ice volume simulated under scenarios A, B, C and E exhibit a similar general behaviour. The fast continental ice volume increase is briefly interrupted by a short re-

Table 1
CO_2 scenarios for the future

Label		Comments
A	Constant CO_2 concentration (210 ppmv)	This forcing is likely to bias climate towards cold conditions
B	Past CO_2 variation as recorded in the Vostok ice core [58] shifted by 131 kyr	CO_2 concentration close to 260 ppmv until 19 kyr AP
C	Past CO_2 variation as recorded in the Vostok ice core [24] shifted by 415 kyr	CO_2 concentration close to 260 ppmv until 11 kyr AP
D	From the threshold model of D. Paillard (personal communication)	CO_2 concentration remains higher than 280 ppmv over the next 50 kyr
E	From the threshold model of D. Paillard (personal communication)	CO_2 concentration already lower than 220 ppmv at 20 kyr BP

versal and followed by a slower increase towards the next glacial maximum, reached shortly after 100 kyr AP.

These variations in ice volume confirm the conclusion already drawn. Over the last 11 kyr, the high CO_2 concentration counteracts the effect of the decreasing insolation (this is only possible because insolation changes are small) and ice volume does not increase. Then over the next 50 kyr insolation does not reach minima low enough to drive climate towards glaciation, although CO_2 is decreasing. It is only after 50 kyr AP, when insolation reaches a stronger minimum and CO_2 has reached glacial level, that the ice sheets can start to grow again.

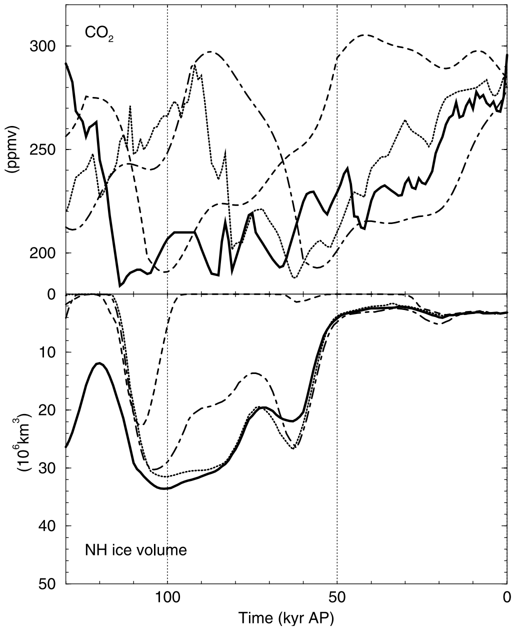

Fig. 6. CO_2 forcings (top) and response of the model (Northern Hemisphere continental ice volume, bottom) over the future. Scenario B, solid line; scenario C, dotted line; scenario D, dashed line; scenario E, dot-dashed line (see Table 1).

An important and robust feature of the simulated future is the long interglacial we are already living in. This feature is independent of any human activity. Moreover, it is mostly constrained by the forcings (insolation and CO_2 concentration) of the last 10 kyr. Therefore it is very unlikely that the Earth could avoid it. Another general feature of these simulations, under natural CO_2 forcing, is the occurrence of the next glacial maximum at about 100 kyr AP followed by a deglaciation (partial or total) at about 120 kyr AP.

4. Discussion and conclusion

MIS 11, some 400 kyr ago, was identified to be a good analogue for future climate changes [6]. Different simulations were performed for the MIS 11 time interval to identify the conditions constraining the length of this simulated interglacial. The future climate can then benefit from the conclusions drawn on MIS 11, its analogue. During MIS 11 a good phasing between CO_2 concentration and insolation variations is required to drive the climate system into glaciation, mostly because insolation changes are small. In other words, if the insolation decrease is not strengthened by a CO_2 concentration decrease during MIS 11, the climate remains in the interglacial state with no or small continental ice sheets for more than 40 kyr. The same applies for the future, although there is a major difference in our interpretation in that case. Indeed, we already know that insolation decrease is not strengthened by CO_2 concentration decrease. Therefore we conclude that our interglacial will remain stable for at least 40 kyr in natural conditions. The climate simulations performed under different scenarios of future CO_2 concentration confirm this conclusion.

According to IPCC, human activities influence the global climate. More precisely, it is suggested that *most of the observed warming over the last 50 years is likely to have been due to the increase of greenhouse gas concentrations* [43]. IPCC scenarios suggested that CO_2 concentration could become as high as 1000 ppmv at the end of the 21st century as a result of fossil fuel burning. A conservative global warming scenario, based on an increase of the CO_2 concentration up to 750 ppmv within 200 years and a come-back to natural conditions in 1000 years, leads to the complete melting of the Greenland ice sheet between roughly 10 and 14 kyr AP [39]. Small differences between the *natural* and the *global warming* experiments persist after 100 kyr AP. A less conservative scenario, assuming a higher fossil fuel contribution to CO_2 concentration over a longer time interval, i.e. CO_2 increasing up to 1130 ppmv at 2275 AD and then recovering very slowly, leads to a full melting of the Northern Hemisphere ice sheets over the next 150 kyr and ice sheets smaller than 20×10^6 km^3 over the next 500 kyr.

The potential collapse of the Greenland ice sheet related to global warming is suggested by ice sheet models of different complexities under either increased temperature [44,45] or doubled CO_2 concentration [46–49]. With the LLN 2-D NH climate model, the long-term impact of an instantaneous melting of the Greenland ice sheet would be an ice-free Northern Hemisphere over 50 kyr AP at least, with further behaviour depending on the CO_2 concentration. Moreover, the consequences of this melting can still be recognised at 100 kyr AP [39] in a very conservative case.

All these simulations taking into account the potential impact of human activities on climate reinforce the conclusions already drawn for *natural climate*. The next 50 kyr are characterised by small – if any – Northern Hemisphere ice sheets. No significant variability in the continental ice volume is simulated during that time. The behaviour of the ice sheets after 50 kyr depends on how much and for how long the atmospheric CO_2 concentration is influenced by human activities. Even if CO_2 concentration comes back rapidly to a *natural* concentration, the amount of continental ice only becomes similar to the natural values after 100 kyr AP.

Other issues could also affect future climate. North Atlantic marine cores have recorded abrupt events, which punctuated the last deglaciation [50,51]. Some of them are likely a consequence of a freshwater pulse released by melting ice sheets, either Laurentide or Fennoscandian ice sheets, or possibly the Antarctic ice sheet [52]. Such discharges could perturb the ocean circulation. However, they are recorded at times when Northern Hemisphere ice sheets were large. Therefore, further studies should address the question whether such events could also occur in the future and whether iceberg outbursts could significantly modify North Atlantic deep water production and thus set the stage for a nearer glaciation [53–55]. Similarly, it was also suggested that an increase in the river discharge to the Arctic Ocean could also impact on the ocean circulation and consequently on the climate [56].

On the other hand, the response of the Antarctic ice sheet, in particular the West Antarctic Ice Sheet, under global warming conditions needs also to be studied. Experiments with a dynamic 3-D thermomechanic ice sheet model performed under increased CO_2 concentration conditions brought to light that during the next century the Antarctic ice sheet is likely to grow but in the longer term it will contribute positively to the world-wide sea-level stand [57].

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