COMMENTARY ON "THE ANTHROPOGENIC GREENHOUSE ERA BEGAN THOUSANDS OF YEARS AGO"

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Abstract. Bill Ruddiman (*Climatic Change*, **61**, 261–293, 2003) recently suggested that early civilisations could have saved us from an ice age because land management over substantial areas caused an increase in atmospheric CO_2 concentration. Ruddiman suggests a decreasing "natural course" of the Holocene greenhouse gases concentrations and sea-level by referring to analogous situations in the past, namely the last three interglacials. An examination of marine isotopic stage 11 would perhaps make Ruddiman's argument even more thought-challenging. Yet, the hypothesis of a natural lowering of CO_2 during the Holocene contradicts recent numerical simulations of the Earth carbon cycle during this period. We think that the only way to resolve this conflict is to properly assimilate the palæoclimate information in numerical climate models. As a general rule, models are insufficiently tested with respect to the wide range of climate situations that succeeded during the Pleistocene. In this comment, we present three definitions of palæoclimate information assimilation with relevant examples. We also present original results with the Louvain-la-Neuve climate-ice sheet model suggesting that if, indeed, the Holocene atmospheric CO_2 increase is anthropogenic, a late Holocene glacial inception is plausible, but not certain, depending on the exact time evolution of the atmospheric CO_2 concentration during this period.

The debate about the reason for the steady increase in CO_2 concentration between the Early Holocene (260 ppmv, 8000 years ago) and the pre-industrial era (280 ppmv, 300 years ago), recently spiced up by Bill Ruddiman's hypothesis that this increase could be due to early land management (Ruddiman, 2003), illustrates well two conceptions of understanding and forecasting climate dynamics.

On the one hand, experts in biogeochemical cycles have shown that the increase in atmospheric CO_2 concentration during the Holocene is easily explained by a set of reasonable hypotheses about natural changes in land carbon sequestration, lysocline depth and sea-surface temperature in response to the orbital forcing. Seemingly, the only debate is about the respective contributions of these three factors (Indermühle et al., 1999; Brovkin et al., 2002; Joos et al., 2004). The MoBidiC model (Crucifix and Joos, 2004) simulates for its part no more than a 4 ppmv increase in CO_2 concentration in response to the orbital forcing during the Holocene (Figure 1, previously unpublished results). Unfortunately, these estimates are associated with considerable uncertainties. Thorne et al. (2004, submitted) recently termed 'structural uncertainties' errors associated with the hypotheses used in a model-based analysis process (it covers, in this case, aspects as various as inferring

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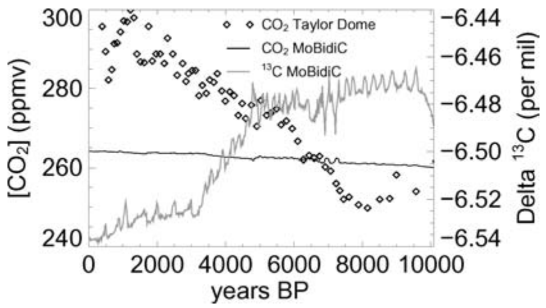

Figure 1. Time evolution of atmospheric CO_2 concentration and $\delta^{13}C$ ratio simulated by MoBidiC in response to the orbital forcing during the Holocene. Initial conditions are atmosphere, vegetation, ocean circulation and carbon balance in equilibrium with an atmospheric CO_2 concentration of 260 ppmv, $\delta^{13}C = 6.5$ per mil and orbital forcing of 10,000 years ago. The model carbon cycle includes equations for vegetation productivity and growth, ocean soft tissue carbon production (particulate and dissolved) and remineralisation at depth, biogenic carbonate production and dissolution, and air-sea gas exchanges. The ocean alkalinity is constant. The CO_2 concentration data obtained from the Taylor Dome ice core by Indermühle et al. (1999) are displayed as a comparison.

past alkalinity from preservation records, using zonally averaged equations and a certain tracer diffusion scheme, or neglecting coral-reef build-up). They are, by definition, difficult to identify and to quantify. Given our present level of understanding of global carbon cycling, it is certainly fair to argue that the sign of the natural trend in CO_2 during the pre-industrial Holocene is not sufficiently constrained by models alone.

The other approach, followed by Bill Ruddiman, is to scrutinise the past and look for situations analoguous to the present-day. The sledgehammer argument is "Why does a CO_2 rise similar to the Holocene one fail to occur on all three previous interglacials?" But are the previous interglacials real analogues?

The choice of an analogue is made by reference to a set of variables estimated to be relevant for describing the evolution of the global climate system. Continental ice volume is surely one of these. Observations have shown that the Last Glacial Maximum – during which the orbital forcing was very similar to today (Berger, 1978) – is associated with a reduced CO_2 concentration (Petit et al., 1999), a substantial cooling of the ocean surface (Sarnthein et al., 2003), a reduction of the ventilation of the North Atlantic deep Ocean (Duplessy et al., 1988), absence of boreal forests (Bigelow et al., 2003) and large permafrost areas (implying frozen wetlands) (Renssen and Vandenberghe, 2003; Kondratjeva et al., 1993). Computer experiments have also shown that large ice sheets modify the dynamics of the atmosphere considerably (Kageyama et al., 1999); the sea-level drop impacts on the primary productivity of coastal ecosystems (Giraud et al., 2003) as well as on coral reefs (Ridgwell et al., 2003). There are thus many sources of interaction between the carbon cycle and ice volume. On the other hand, both ice volume and CO_2 are ultimately driven by the orbital forcing. Milankovitch (1941) already pointed out that to use one insolation curve (e.g. June insolation at 65°N) has an arbitrary nature.

For example, compared to today, insolation at 65°N 122,000 years ago was larger in July but it was smaller in May (it could be argued that the latter is important for sea-ice melt, for example). There are admittedly several ways round this. Milankovitch resorted to the notion of caloric season. Berger (1979) introduced the concept of insolation signatures, which is based on the time evolution of the insolation seasonal cycle at different latitudes. Hays et al. (1976) directly correlated their deep-sea core records with the orbital parameters. The problem is then that it is almost impossible to describe the link between orbital parameters (say, eccentricity) and ice volume in simple mechanistic terms. Last but not least, the history of CO_2, ice volume and insolation determine the future of the system through its slow-response components (isostasy, deep ocean temperature, sediments).

In light of these considerations, a true analogue of the Holocene would be characterised by the same eccentricity, obliquity, precession, sea-level and CO_2 concentration *histories* as today. The time around 400,000 years ago, slightly before marine oxygen isotopic stage (MOIS) 11.24 (Bassinot et al., 1994), bears interesting similarities with the Holocene from the point of view of the astronomical forcing (Loutre, 2003): eccentricity was very small, and the phase relationship between obliquity and precession, the importance of which was stressed by Berger et al. (1999) and Vettoretti and Peltier (2003b), were similar – but not identical – to today. MOIS 11 is not quite as convincing an analogue as regards ice volume history. There is now evidence that MOIS 11 had a higher sea-level than today, perhaps by 13 m (Droxler et al., 2003 [and references therein]). Furthermore, the amplitude of the previous glacial maximum (MOIS 12) was exceptional and never reproduced since then (Droxler et al., 2003). According to a chronology recently inferred from the EPICA Antarctic ice core (EPICA community members, 2004), it occurred 430 kyr ago, that is, 30,000 years before the analogue for the modern astronomical configuration (while the last glacial maximum occurred 21,000 years ago).

Nonetheless, several characteristics of stage 11 are puzzling and would argue in favour of Ruddiman's hypothesis. According to the Vostok ice core record (Petit et al., 1999), CO_2 *and* sea-level substantially decreased *before* stage 11.24. Therefore, we would like to reformulate Bill Ruddiman's question addressed to modellers : "Have you correctly *assimilated* all the information available from proxy records?".

Assimilation can be understood in its broadest sense. It may simply mean to subjectively include the palæoclimate information in the inference process. It is rather classical in climate dynamics research to challenge a climate model *a posteriori* in situations that have not been tested in the tuning process, such as past climates. The Palæoclimate Modelling Intercomparison Project (Harrison et al., 2002) is specifically devoted to this task. This operation is particularly essential where threshold phenomena, difficult to quantify, are involved. Consider, for example, the Louvain-la-Neuve climate-ice sheet model (Gallée et al., 1991). This model has been shown to simulate a glacial inception at the time of MOIS 5d for

CO_2 concentrations as high as 290 ppmv (Berger et al., 1998). This is in agreement with palæoclimatic data. The LLN model also exhibits a high sensitivity to CO_2 during MOIS 11: Small changes in the time stratigraphy of CO_2 concentration used as forcing, well within uncertainties, may either yield a rapid glacial inception or a long interglacial (Loutre, 2003). Together, these results suggest that the LLN model reasonably well captures the threshold for a glacial inception. Starting from this basis, it has been attempted to get more clues about the validity of Bill Ruddiman's hypothesis of a late Holocene glacial inception as the natural course of climate. We have tested (previously unpublished results, except scenario 1 published in (Loutre and Berger, 2003)) various scenarios of CO_2 evolution during the Holocene consistent the previous interglacials, as suggested by Ruddiman. These are illustrated on Figure 2. The insolation forcing is calculated normally after Berger (1978). Scenario 1 is the Vostok record (Jouzel et al., 1993) until 1 kyr BP, and Vostok shifted by + 131 kyr for the future. All other scenarios assume a CO_2 increase during the last deglaciation as in the latest Vostok record (Petit et al., 1999) but differ between −11 kyr and +40 kyr: *scenario 2* is Vostok shifted by +109 kyr (present-day value as MOIS 5.4); *scenario 3* is Vostok shifted by 303 kyr (present as MOIS 9) and *scenario 4* is Vostok shifted by 228 kyr (present as MOIS 7.4). Note that concentrations between 11 and 6 kyr BP have been slightly adjusted in scenarios 3 and 4 to allow for a smooth transition between the deglaciation and the Holocene. Scenarios 1 to 3 produce a long interglacial. Only scenario 4 has the Northern Hemisphere ice sheets regrowing in the future, probably because the CO_2 is the lowest of all four scenarios between 3 kyr BP and present. In that case, the ice volume culminates at 21 10^6 km^3 as early as 23 kyr after present. These model outputs not only confirm the central importance of the CO_2 concentration over the last 10,000 years in these times of low eccentricity; they also suggest that if the steady CO_2 increase since the early Holocene is really anthropogenic, it is possible – but not certain – that early civilisations saved us from an ice age. In the same line, Vettoretti and Peltier (2003a) have illustrated with slab-AGCM experiments how the last glacial inception imposes constraints on the representation of the present-day hydrological cycle. In their model, the threshold for an immediate (with modern astronomical forcing) glacial inception is below or around 260 ppmv (Vettoretti and Peltier, 2003b). This is not very far from the pre-industrial concentration.

Attempts have been made to formulate the assimilation problem in a more objective and systematic way. Palæoclimate information may be used to constrain model parameters. Hargreaves and Annan (2002) performed thousands of experiments of the last 500,000 years using the Saltzman and Maasch (1990) 0-dimension model. A smart iterative way of adjusting model parameters allowed them to identify values producing a best fit to the timeseries of CO_2 and temperature as inferred from the Vostok ice core record. That 'optimal' model forecasts an immediate cooling of the Earth, with the next glacial maximum in around 60,000 years.

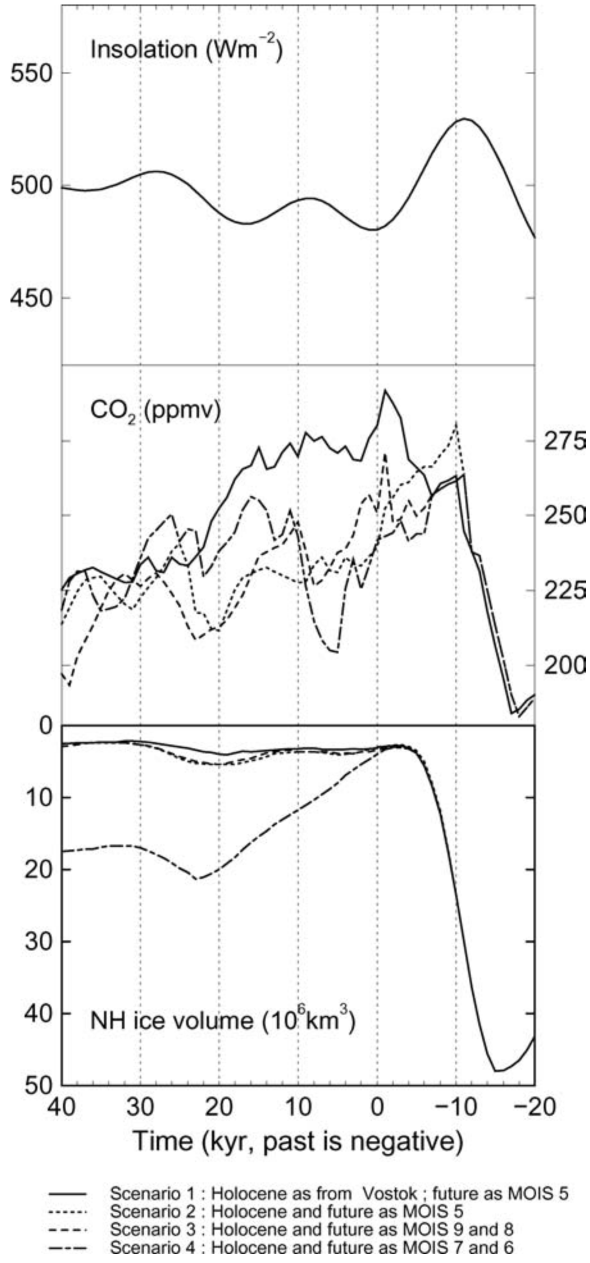

Figure 2. *Top:* Mid-month June insolation at 65°N, *Middle:* CO_2 forcings and *Bottom:* response of the LLN model (Northern Hemisphere continental ice volume) over the last 20 kyr and the next 50 kyr. The different CO_2 scenarios summarised in the legend are explicated in the text.

Palæoclimate experiments have also evidenced a part of climate unpredictability at the millennial time scales related to ocean-atmosphere interactions. For example, Renssen et al. (2003) showed that the temporal response of the ocean circulation to a freshwater discharge in the North Atlantic may radically differ depending on the exact initial conditions of the system. Here, the assimilation problem is posed in terms similar to the weather forecast assimilation problem: How to use the recent palæoclimate information to improve the predictive skills of the model? Matt Collins (cf. Renssen and Osborn, 2003) has proposed a method whereby many realisations of each simulation year are generated under appropriate external forcing variations, and the closest analogue to palæodata for that time is selected before proceeding to the next year of the simulation.

Finally, it is probably best to go as far as possible in the forward modelling process of proxy records. Progress has been made in isotopic and biogeochemistry tracer modelling such that isotopic ratios of carbon and oxygen can be readily simulated. This strategy must be promoted as it will enable us to get the most out of palæoclimate information.

Bill Ruddiman's hypothesis will probably be discussed for years. The point we wished to make here is that model will only provide a valuable response if they are tested and improved to provide a satisfactory behaviour over a broad range of different situations. Palæoclimate modelling is an essential step towards our comprehending of the Earth system, which is a prerequisite to our confidence into climate forecasts. This is the reason why the glacial inceptions that have followed MOIS 5e, 7 and 11 are undoubtedly worth understanding carefully and should also be the object of modelling studies with state-of-the art models.

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