Palaeoperspectives on Global Sustainability

by M. Montoya, V. Brovkin, S. Rahmstorf and M. Claussen

Exploration of palaeoclimate is a challenge for both data and modelling scientific communities. Among scientists, there are sometimes different opinions about the reliability of palaeodata and model simulations. However, in one point there is a strong consensus between both communities: the past, on different time scales, provides us with the best way of validating climate models. Until we can successfully “predict” the past, our models cannot be relied upon for the future. This article discusses research on a broad spectrum of palaeodata archives (ice-core, marine, terrestrial and palynological), as well as climate modelling.

Ice cores provide excellent annual records including both local and global signatures, like CO_2 and CH_4 concentrations. The latter allow a synchronisation of Greenland and Antarctic records, helping to establish the phasing between events in both hemispheres. Marine sediment records, with their extensive coverage, constitute an archive of both surface and deep-ocean conditions, which can be related to past climate and ocean circulation. Terrestrial records allow reconstructions of vegetation, lake levels, and dust, and are hence crucial to obtain information about spatially heterogeneous climatic responses. Varved (annually resolved) lake sediment records, together with tree-ring data, are the major source of information on inter-annual variability in the past for large areas and could provide invaluable information on natural climate variability and its dependence on the mean climatic state.

Palaeoclimate simulations provide insight into the sensitivity of the climate system and hints about the processes and feedbacks responsible for past climatic change, both crucial aspects for future potential anthropogenic climate change. For example, intensified summer monsoons and northward shift of forests in the northern hemisphere at the mid-Holocene (c. 6000 BP) and the last interglacial period (c. 120-130 kyr BP) are evident in many palaeodata. These can be explained, respectively, by the enhanced land-sea temperature gradient and the enhanced summer insolation through the positive sea-ice albedo and vegetation-snow feedback at those times compared to the present. In addition, palaeoclimate simulations provide a tool for model validation, helping to highlight deficiencies of climate models. This is a prerequisite for assessing potential climate impacts due to anthropogenic perturbations of the climate system. One of the main conclusions of the Paleoclimate Modelling Intercomparison Project (PMIP, a PAGES-CLIVAR project, www-lsce.cea.fr/pmip) for the mid-Holocene climate is that although all models simulate wetter conditions over North Africa, most underestimate the precipitation increase estimated necessary to sustain Sahara vegetation and lake levels as pointed by data. In contrast, simulations with intermediate complexity climate models which include an interactive vegetation component reproduce much wetter conditions, suggesting an important role for vegetation and its interaction with the other components of the climate system [1]. A general agreement is also emerging within the palaeoclimatic community that there is a need for a wide range of climate models of different complexity, from conceptual to comprehensive general circulation models, and that it is crucial to incorporate proxies into models that can be directly compared with the palaeodata.

Climatic archives, especially ice-core records, provide a fascinating picture of the past climate of the Earth during the last 400 kyr [2]. The most dramatic features are the glacial-interglacial cycles. Temperature, greenhouse gases and ice-sheet volume show cyclic variations characterised by long cold periods and shorter warm interglacials, within apparently stable bounds. After decades of research, the strength of the astronomical theory of climate, which states that variations in the orbital parameters of the Earth are the ultimate drivers of glacial-interglacial cycles [3], has been clearly demonstrated through a wealth of data. Yet, it remains unclear which processes and feedbacks have maintained the natural Earth System within

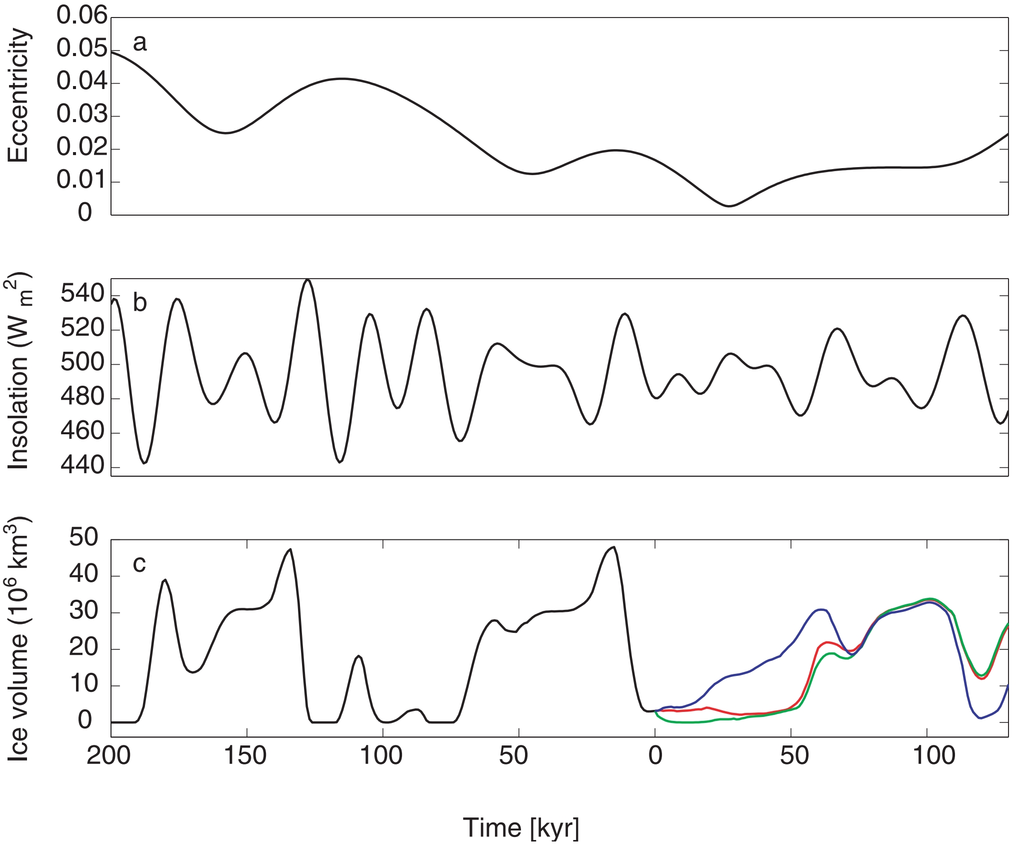

Figure 1. Long term variations of (a) eccentricity and (b) June insolation at 65°N (from [4]) and (c) simulated ice volume for the past (black, from [10]) and future (from [5]). For the future, three CO_2 scenarios were used: last glacial-interglacial values (red), a concentration of 750 ppmv (green) and a concentration of 210 ppmv (blue). Data kindly provided by M.-F. Loutre.

its bounds during the last 400 kyr. Identifying these would be a major step in our understanding of the dynamics and the resilience of the climate system, and whether human activity might perturb the Earth System from its current apparently stable mode of operation.

A question related to global sustainability concerns is when the next glaciation can be expected. The fact that the length of the Holocene (i.e. the last c. 10 kyr) has already surpassed that of some previous interglacials has led some previous authors to speculate that this should imply its imminent end. In contrast, the astronomical theory of climate predicts an exceptionally long duration of the present interglacial as a consequence of the particular orbital forcing during the next 50 kyr [4,5]: eccentricity is approaching a value close to zero, its minimum value being attained in 20 kyr (Figure 1). Based on this, an important message for the future is the fact that we might be entering a very special period in which one of the forcing mechanisms, insolation, will scarcely vary, leaving a main role for CO_2. Model simulations [5] suggest a threshold CO_2 value exists above which the Greenland Ice Sheet disappears (Figure 1). This would mark the end of the Quaternary ice-age and the beginning of the so-called “Quinternary”, an almost ice-free climate regime.

In spite of the impressive achievements of the astronomical theory of climate, some crucial aspects require further research into the dynamics of the climate system. The amplifying feedbacks contributing to glacial inception are not fully understood. In addition, the processes behind glacial-interglacial CO_2 fluctuations, which are an intrinsic component of glacial-interglacial cycles, remain unclear. A number of mechanisms have been proposed, yet all of them are beset with problems. In reality, several different mechanisms might operate in combination.

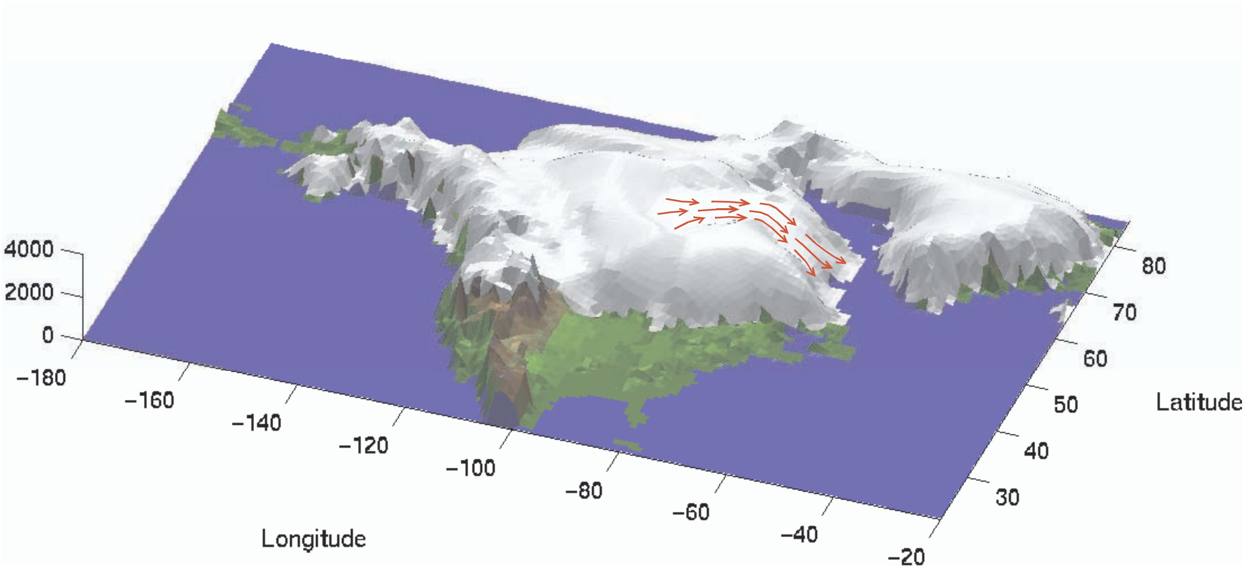

Figure 2: Laurentide ice-sheet thickness and extent simulated by the CLIMBER-2 Earth System Model including the SICOPOLIS ice-sheet model for constant Last Glacial Maximum climatic conditions. The red arrows indicate the major ice flow path during the Heinrich event shown in this snapshot. Data kindly provided by R. Calov [9] and plotted by I. Schramm.

Solving this puzzle is a key to answer the question of how much CO_2 can be sequestered by the ocean on a long time scale.

> “Model simulations suggest a threshold CO_2 value exists above which the Greenland Ice Sheet disappears. This would mark the beginning of the so-called “Quinternary”, an almost ice-free climate regime.”

An additional fascinating feature revealed by the ice-core record and established as well in high resolution marine sediment cores is the large and abrupt climatic changes, Dansgaard-Oeschger (D/O) and Heinrich (H) events, evident during the past glacial period. In contrast, the Holocene appears as a comparatively stable period, and it is thought that the development of human agriculture within the Holocene did not occur by chance, but was favoured by the optimal climatic conditions. Could large-scale perturbations drive the system into a different mode of operation? Answering this question requires an understanding of the reasons for the different stability of the climate of the last glacial cycle compared to today’s, and, ultimately, the mechanisms behind abrupt climate change. A consistent picture is emerging from the palaeorecord and simulations with intermediate complexity climate models in which the Atlantic ocean circulation plays the role of a non-linear amplifier. D/O events are characterised by different modes of the Atlantic thermohaline circulation, which are linked to different convective sites in the North Atlantic [6]. Some discussions concern the role played by the tropics. As evidenced by the ice-core records, almost all D/O events in Greenland were associated with CH_4 variations. Due to the fact that, during the last glacial period, high latitude CH_4 sources were covered by ice sheets, low latitude wetlands were initially assumed to have been responsible for such CH_4 variations. However, box models suggest that CH_4 changes during the D/O events originated through a very strong reaction of wetlands from high latitude sources, probably from Eurasia [7].

Heinrich events, in turn, have been simulated by a variety of models by invoking instabilities of the ice-sheets once a given ice-volume threshold has been surpassed [8]. Recently, an intermediate complexity climate model has been able to simulate, for the first time, Heinrich events as a result of internal ice-sheet instabilities (Figure 2, [9]). But crucial questions remain: even if this picture of abrupt climate change and the crucial role of the thermohaline circulation were correct, the challenge is to determine what is the ultimate trigger of the thermohaline variations. An additional puzzle refers to the mechanisms behind the Younger Dryas (a rapid climate change event that occurred during the last deglaciation of the North Atlantic region, c. 11,6 kyr BP): which mechanisms, together with meltwater discharges, were responsible for the extreme cooling given the high CO_2 concentrations at that time?

The 21st century will either witness the transition to global sustainability or the further separation of cultures and generations into winners and losers under accumulating environmental and developmental pressure. One important aspect in the discussion of global sustainability concerns the resilience of the natural Earth System to large-scale natural and anthropogenic perturbations such as those related to variations in solar luminosity, volcanic activity, land use, and greenhouse gas emissions. Further exploration of the role these forcings played in the past requires a joint effort by the data and modelling communities. It is now generally recognised that there is no direct palaeoanalogue of potential future climate change. Nevertheless, there is much to be learnt about the dynamics of the Earth System by exploring its history.

Marisa Montoya
Victor Brovkin
Stefan Rahmstorf
Martin Claussen
Potsdam Institute for
Climate Impact Research,
P.O. Box 601203,
Telegrafenberg,
D-14412 Potsdam,
Germany
E-mail: montoya@pik-potsdam.de

Footnote: This article is based on discussions at a workshop titled ‘Paleoperspectives on Global Sustainability’ in the framework of the First Sustainability Days at the Potsdam Institute for Climate Impact Research (September 28th - October 5th 2001). The meeting brought together about forty palaeoclimatologists in an attempt to extract the main lessons that can be learnt from the past.

References

1. Ganopolski A, Kubatzki C, Claussen M, Brovkin V, Petoukhov V. (1998). The influence of vegetation-atmosphere-ocean interaction on climate during the Mid-Holocene. Science 280: 1916-1919
2. Petit JR et al. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399: 429-436
3. Milankovitch M. (1941). Kanon der Erdbestrahlungen und seine Anwendung auf das Eiszeitenproblem, Belgrade (New English Translation, 1998, Canon of Insolation and the Ice Age Problem, 636 pp., Alven)
4. Berger AL. (1978). Long term variations of daily insolation and quaternary climatic changes, J. Atmos. Sci., 2362-2367
5. Loutre MF, Berger A. (2000). Future climatic changes: Are we entering an exceptionally long interglacial? Climatic Change 46: 61-90
6. Ganopolski A, Rahmstorf S. (2001). Simulation of rapid glacial climate changes in a coupled climate model. Nature 409: 153-158
7. Dallenbach A. Blunier T, Fluckiger J, Stauffer B, Chappellaz J, Raynaud D (2000). Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Last Glacial and the transition to the Holocene. Geophys. Res. Lett. 27: 1005-1008
8. Wang Z, Mysak LA. (2001). Ice Sheet-Thermohaline Circulation Interactions in a Climate Model of Intermediate Complexity. J. Oceanogr. 57: 481-494
9. Calov R, Ganopolski A, Petoukhov V, Claussen M, and Greve R. (2002). Large scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model. Geophysical Research Letters, accepted.
10. Berger A, Loutre MF, Gallee H. (1998). Sensitivity of the LLN climate model to the astronomical and CO_2 forcing over the last 200 kyr. Climate dynamics, 14, 615-629