

Using Model Hierarchies to Better Understand Past Climate Change*

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Abstract—As soon as atmospheric general circulation models (AGCMs) have been operational for present or future climate studies, they have also been used to simulate past climates. The goal of this type of exercise has always been twofold: 1) to validate the models' ability to simulate climates different from the present one; 2) to understand the mechanisms that lead to past climate changes depicted by the numerous marine, continental and glaciological records. In the Paleoclimate Modelling Intercomparison Project (PMIP), the simulations from up to 18 different AGCMs have been compared to climate reconstructions for two periods: the Mid-Holocene, 6,000 years ago, and the Last Glacial Maximum, 21,000 years ago. Examples of the PMIP results for each period are presented here. Then, taking these PMIP results as a basis, we discuss the increasing complexity that can be taken into account in paleoclimate modelling:

- Increase in the number of components of the climate system taken into account: complex models can now include not only the atmosphere, but also the oceans and the vegetation, allowing analyses of the feedback from these components onto the atmosphere, of their role in the establishment of climates different from ours. Taking a larger number of climate system components into account allows using more data for the validation of the models rather than for their boundary conditions.
- Increase in the duration of the numerical experiments to study climate transitions rather than only equilibria: models including simpler representations of some components of the climate system are less expensive to be run than the comprehensive general circulation models mentioned above and give the opportunity of studying not only climate equilibria, but also climate transitions. The simplicity of this type of models and their low running cost allow the modellers to carry numerous sensitivity experiments to explore the importance of one forcing factor or one parameterisation.
- Increase in the spatial scale of the simulations: the resolution of the models used in paleoclimate studies has improved, following the increase of super-computer performances. However, the spatial scale of global circulation

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models is still much larger than the scale that would be relevant, for instance, to understand the data in their local context. Applying smaller scale models (such as nested models, mesoscale models for the atmosphere, or models for individual glaciers or lake basins) to paleoclimate studies has already started and will help improve our understanding of the small scale-phenomena that are important for the behaviour of the proxies that record paleoclimates, as well as for the coupling between the atmosphere and some other components of the climate system.

These developments in paleoclimate modelling will be illustrated using results from the paleoclimate modelling team at Laboratoire des Sciences du Climat et de l'Environnement as well as from other groups working on these themes. They illustrate how using the hierarchies of models presented above helps us better understand the mechanisms at the basis of the climatic changes observed in the paleorecords, and therefore be more confident in our scenarios for the future climate evolution.

INTRODUCTION: RESEARCH THEMES, TOOLS AND APPROACHES IN PALAEOCLIMATE MODELLING

Palaeoclimatic records from the oceans, the continents, and the ice-sheets show that the Earth's climate has significantly varied in the past. For instance, 21,000 years ago, at the Last Glacial Maximum (LGM), northern North America and northern Europe were covered by ice-sheets several kilometres high. This striking difference with the present situation is not limited to the ice-sheet distribution. Marine records have pointed towards much colder temperatures and more extensive sea-ice cover, particularly in the North Atlantic. Continental records have shown that the land surface characteristics were also strongly different from today, with, for example, occurrence of permafrost as far south as northern France, and steppic vegetation over much of Europe in regions where forests grow today. The numerous paleoclimatic records at our disposal today show that during the Quaternary (the last two million years) the Earth climate has oscillated between glacial states such as LGM state described above, and warmer, interglacial states such as the present one. Past climatic variations therefore offer a good and actually unique test ground to our knowledge of the mechanisms of climate change.

At the time-scale of the 40 or 100 thousand-year glacial-interglacial cycles, the climate system is thought to respond to the fluctuations in incoming insolation linked to the variations of the Earth orbital parameters (Milankovitch theory). Simple models (such as the model presented in Paillard (1998)) actually prove that it is possible to derive e.g. the global ice-volume evolution over many glacial-interglacial cycles as a function of summer insolation. Such models demonstrate that threshold and hysteresis mechanisms are essential to "transform" the known insolation forcing into a realistic ice-volume evolution. However, their goal is not to explicitly represent the physical phenomena at the basis of these relationships.

At the other end of the model complexity range, models taking a maximum number of physical mechanisms into account, such as general circulation models

for the atmosphere or the ocean, have been used to study the climate of a given period (“snapshot” experiments), generally at equilibrium with a set of boundary conditions appropriate for that period. For instance, in the framework of the Palaeoclimate Modelling Intercomparison Project (PMIP, Joussaume and Taylor, 1995), simulations of the climates of the Mid-Holocene (6,000 years BP) and LGM have been performed using the same atmospheric circulation models that are used in studies of present or future climate. Such numerical experiments are designed to study the impact of one or several changes in the boundary conditions on the simulated climate. Because these models are based on the representation of basic physical mechanisms, one can study, through such experiments, the mechanisms responsible for a difference in climates simulated under different boundary conditions. However, very long simulations cannot be performed using such complex models, which therefore cannot be used to explicitly study the temporal evolution of the palaeoclimatic reconstructions.

Between these two extremes, other models, the so-called “models of intermediate complexity”, have been developed, that can typically be used to simulate climate evolutions over thousands of years. These are particularly appropriate to study the variability on the millennial scale, within the glacial-interglacial cycles.

All these types of models are useful, in their own way, in increasing our understanding of the climatic variations that have occurred in the past. The palaeoclimate modelling team at Laboratoire des Sciences du Climat et de l’Environnement has chosen to use at best such a hierarchy of models, to understand the climate of a given period with spatial and physical detail with general circulation models on the one hand, the large millennial climatic variations during glacial times using a model of intermediate complexity, variations on the glacial-interglacial cycle scale using conceptual models. Parallel to these modelling activities, careful comparisons to data are conducted. These will be discussed independently for each example treated in the text.

THE CLIMATE OF THE LAST GLACIAL MAXIMUM (21,000 YEARS AGO)

The climate of the Last Glacial Maximum was, on a global average, colder than the present climate. Different proxy records show that this cooling is far from being geographically uniform: in the tropics, it generally amounts to less than 10°C, while in the extratropics, differences have been evaluated to as much as 25°C in Europe. This difference between the climate sensitivity of the tropics and that of the mid- and high latitudes for a colder-than-present climate can be interestingly paralleled to the different sensitivities in the case of a warming induced by a higher concentration in greenhouse gases.

Palaeoclimate modelling intercomparison project experiments

In the framework of PMIP, two types of LGM climate simulations have been performed. Both use the same boundary conditions for the ice-sheet reconstructions (Peltier, 1994), the CO₂ concentration (set to 200 ppm) and the orbital parameters

(set to those for 21,000 years ago). Some models used prescribed Sea Surface Temperatures (SSTs, derived from the CLIMAP (1981) data set); others were coupled to a slab ocean model to compute their SSTs, under the assumption that the oceanic meridional heat fluxes were unchanged. Both approaches have their weaknesses: while the former is strongly dependent on the CLIMAP reconstruction, which has been much debated since its publication and is currently being revised, the latter is based on an assumption that we know not to be valid. However, this was exactly the same type of model, used with the same assumption, that was used for climate predictions until the very recent development and use of fully coupled atmosphere-ocean general circulation models. The LGM simulations therefore represented a good test of the models' ability to represent such an extreme climate, under these assumptions.

In the tropics

Palaeoclimate reconstructions of the LGM temperatures show that in the tropics, the cooling was slightly larger over land than over the ocean: data point towards anomalies in the annual mean temperatures of -2 to -7°C over land, and mostly -1 to -3°C over the ocean (these reconstructions, using the alkenone proxy, are independent from the CLIMAP SSTs). Can the models reproduce these results? Pinot *et al.* (1999a) show that the prescribed SST experiments (anomaly in SST of -0.7°C imposed by the CLIMAP SSTs) show an annual mean cooling over land included between -1.5 and -3.5°C . So, with the CLIMAP SSTs as a boundary condition, the models cannot reproduce the range as estimated from pollen data. On the other hand, the computed SST runs yield ocean temperature anomalies included between -1 and -4°C and land temperatures between -1.5 and -5.5°C . So, a first conclusion could be that computed SST simulations are satisfactory, in the sense that they can reproduce this difference of behaviour between the ocean and land data. However, looking at the results on a regional scale, Pinot *et al.* (1999) showed that some discrepancies remained, even in this type of simulations, on a regional scale.

In Europe and western Siberia

The European climate at LGM was much affected by two factors: on the one hand the presence of ice-sheets over northern Europe, but also over northern North America, and on the other colder conditions at the sea surface, at least as described by the CLIMAP (1981) reconstructions. From the results of all the PMIP simulations, it appears that the impact of the Fennoscandian ice-sheet is greatest in summer, via the albedo effect, while the extensive CLIMAP sea-ice cover has a strong impact in winter (Fig. 1 for the prescribed SST simulation results, Kageyama *et al.* (2001) for more details). Indeed, computed SST simulations yield warmer-than-CLIMAP sea-surface temperatures over the North Atlantic, and warmer temperatures over western Europe (see also the simulation of Pinot *et al.* (1999) using a LGM "warm" North Atlantic SST reconstruction).

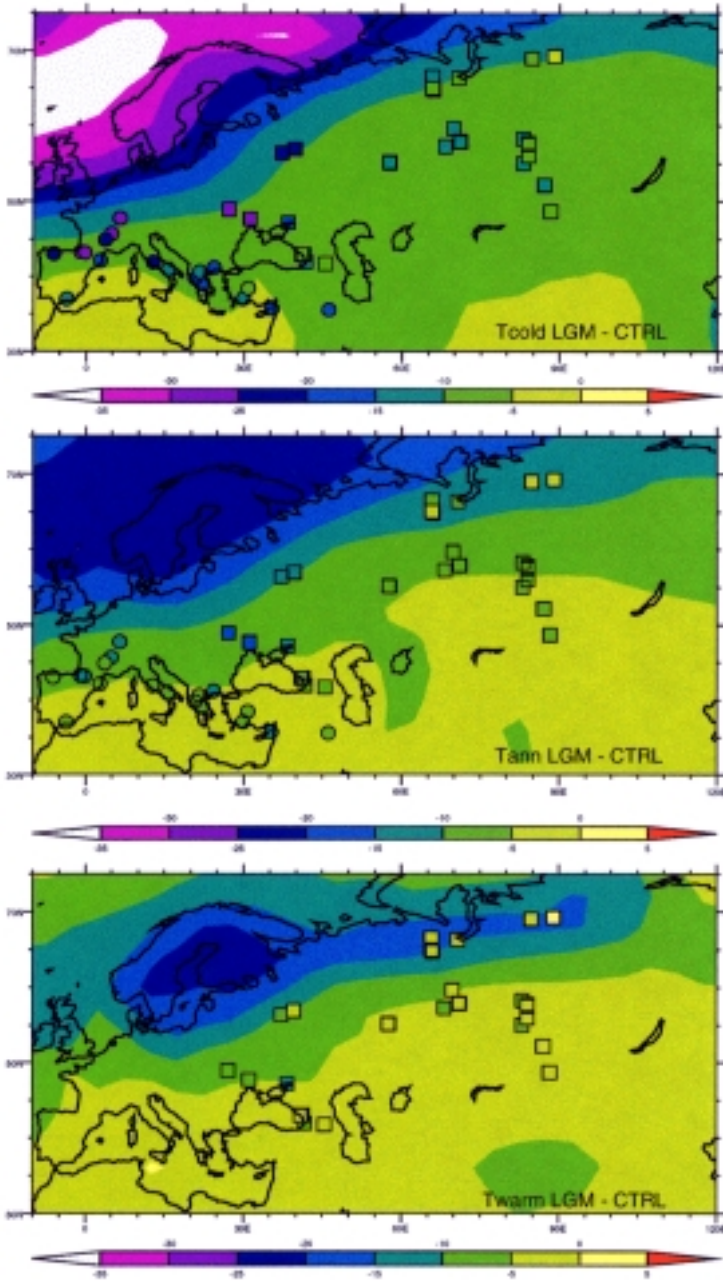


Fig. 1. Model-data comparison for the Last Glacial Maximum Climate over Europe (Kageyama *et al.*, 2001). Background: average of all the prescribed sea-surface temperature simulations; dots: estimates for the same variable as reconstructed from pollens (Peyron *et al.*, 1998; Tarasov *et al.*, 1999). Top: temperature of the coldest month (surface air temperature, LGM-CTRL); middle: mean annual temperature; bottom: temperature of the warmest month.

Kageyama *et al.* (2001) give more detail on the PMIP LGM climate simulations over Europe. The range of the model results, in temperature as well as in precipitation, is fairly large (sometimes up to 10°C for the temperatures). However, when compared to the pollen-based thermal and hydrological estimates from Peyron *et al.* (1998) and Tarasov *et al.* (1999), all models simulate too warm temperatures in winter over western Europe and too cold temperatures in summer over northwestern Siberia. The discrepancy over Europe is unlikely to be explained by only one cause. Rather, there are several candidates that were not taken into account in the PMIP simulations and that could be responsible for it: briefly, those are permafrost, which was more extensive at the LGM, changes in vegetation cover, the presence of more atmospheric dust. New, warmer reconstructions of the SSTs over the North Atlantic are actually likely to be linked to warmer temperatures over western Europe, as shown by Pinot *et al.* (1999b). The discrepancy over northwestern Siberia is easier to explain: over this region, an ice-sheet is prescribed as a boundary condition to the models, which is contradictory to the fact that model results are actually compared to pollen-based estimates. New ice-sheet reconstructions are presently being discussed, which is likely to reduce this difference between model results and paleoreconstructions.

However, on a smaller scale, this problem could remain, since paleodata retrieved at one site are essentially local, in the sense that they can be influenced by local features such as topography, land surface type etc. This type of features, on a fine spatial scale, cannot be resolved by general circulation models even if their resolution substantially increases. An interesting approach to this problem is to use nested mesoscale models or zoom models to study a particular region, as has been done in a recent study of the climate at the vicinity of the waning Laurentide ice-sheet 11,000 year ago (Hostetler *et al.*, 2000). Another approach is to use specific models for each type of data to which model results are compared, such as a biome model for the vegetation, a lake model for the lake levels. These models have been used to transform the output from GCMs in results directly comparable to data, and to find the range in a particular variable that can explain an anomaly in the proxy that is considered (for a recent review on these models that can be used as intermediates between GCMs and proxy data, see Kohfeld and Harrison, 2000).

THE CLIMATE OF THE MID-HOLOCENE (6,000 YEARS AGO)

Paleodata show that the climate of the Mid-Holocene is characterised by enhanced monsoons over India and Africa, the latter being associated with the so-called “green Sahara”, meaning that the desertic area of North Africa was much reduced at that time, being covered by steppic vegetation and, to the south of the zone, by extensive lakes. Vegetation at high-latitudes was also different from today’s, the tundra-taiga limit being located more to the North than at present. Both aspects, tropical and high-latitude climates, have been or are currently being studied in the PMIP project, but the following will focus on the results for the African climate (Fig. 2).

Although the Mid-Holocene climate was generally warmer than today, it is not a analogue to a climate under larger CO₂ concentrations such as the situation which we predict for the future. The CO₂ concentration was lower than today (280 ppm) and the main forcing for the climate differences was insolation, with a more contrasted seasonal cycle than today in the northern hemisphere (5% more/less) insolation in summer/winter compared to the present situation). However, it is an important test for the models to check their ability to simulate a climate warmer than the present one.

PMIP experiments: an enhanced monsoon, but not strong enough to get a greener Sahara

The PMIP experiments for the Mid-Holocene climate consisted in a simple sensitivity test to the insolation of 6,000 yr BP and a preindustrial level of CO₂. The SSTs were kept to the present ones and the vegetation cover and surface type representation were kept similar to the present-day simulations.

The main result from the PMIP comparison for this period is that all models produce a warming of the northern hemisphere continental interiors on the one hand, and a strengthening of the monsoon over Asia and Africa (Joussaume *et al.*, 1999). However, even though the sensitivities of the models are different, none of them actually produce the change in precipitation inferred from the palaeoreconstructions of the Mid-Holocene vegetation. This could well be due to the simplicity of the design of the experiments, which did not include vegetation cover changes, nor ocean temperature changes.

Coupling to the ocean and to the vegetation

From these experiments, complementary runs using more complex models have been run at LSCE (Braconnot *et al.*, 2000a, b). The IPSL fully coupled ocean-atmosphere model was first run under the conditions of 6,000 years ago set in PMIP (insolation + CO₂). Compared to the response of the atmosphere-only model (Fig. 2, top), this had the effect of strengthening moisture advection to the Africa interior (Fig. 2, middle). Indeed, the ocean's response was delayed compared to the atmosphere's, and this acted to strengthen the land-ocean gradient important for the existence of the monsoon. Then, the response of the BIOME1 (Prentice *et al.*, 1992) model to this anomaly was computed, feedbacked to the OAGCM, and the iteration was repeated another time, for the biome model and the OAGCM to be nearer to equilibrium. Adding the vegetation feedback has the effect of increasing the precipitation even more (Fig. 2, bottom), and of lengthening the rainy season, by local recycling as well as by inducing more advection (Braconnot *et al.*, 1999). This yielded results much nearer to the paleobiomes reconstructions than the PMIP experiment. This approach, using different types of models, AGCM, AOGCM, AOVGCM, is very useful in determining the role of each component in the climate anomalies.

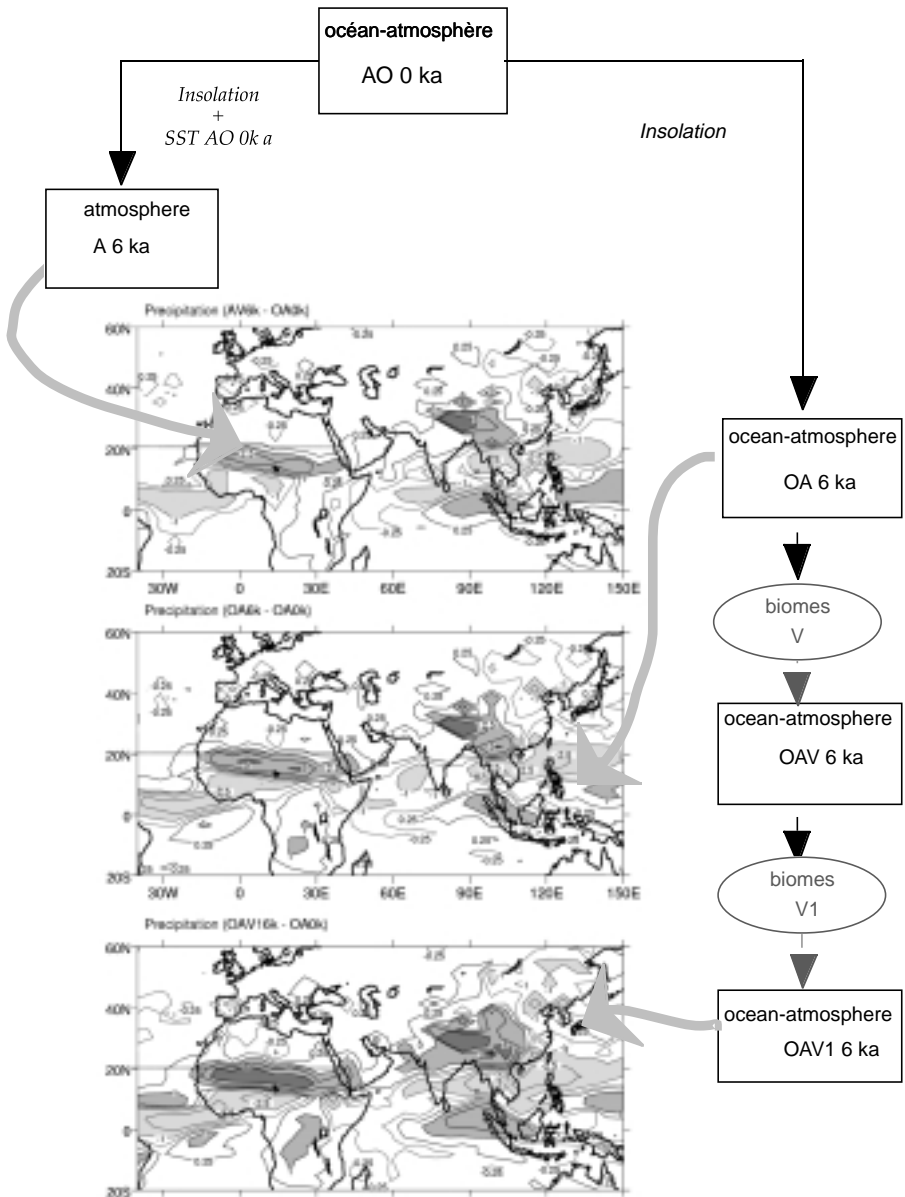


Fig. 2. Experimental design and mid-Holocene changes in precipitation as simulated with the atmosphere alone model (top), the coupled ocean-atmosphere model (middle), and the coupled ocean-atmosphere-biome model (bottom). Values are in mm/day.

Transient experiments with simpler models

Palaeoclimate reconstructions are often very interesting because of their temporal evolution, which cannot be approached via GCMs. Using just timeslices from these reconstructions is very restrictive, and one of the major goals in palaeoclimate modelling is to understand this temporal evolution of the proxy data, not only the climate of particular times. Using models that are simpler than GCMs, in the sense that they do not resolve e.g. the meteorology everyday but parameterise the effects of the transients on the moisture transport on at least the monthly time scale, makes a model appropriate for longer timescale studies. The CLIMBER model (Petoukhov *et al.*, 2000), developed at the Potsdam Institute for Climate Impact Research, is an example of such a model. The transient simulation of the Holocene climate (9,000 years ago to now) by this model shows the capacities of such a model, that comprises simple representations of the atmosphere, the oceans, the vegetation (Claussen *et al.*, 1999).

CONCLUSIONS AND PERSPECTIVES

Palaeoclimates are the only way to evaluate climate models against a climate that has happened and to which the model has not been adjusted. Understanding past climate changes is also a challenge for modellers, a challenge that is renewed everytime new reconstructions come out and present new phenomena. Each problem has specific models associated with it, and the list of models that are useful in the interpretation of palaeodata would be virtually as long as the list of data types (marine sediments, ice-cores, pollen, lakes, etc.). An approach using complementary models, hierarchies of models, is very useful in paleoclimate modelling, to get from the large scale to the fine one, to include and analyse the role of individual components of the climate system, to compute variables that can be more directly compared to paleodata from the results from one model. Such integrated model approaches are and will remain very useful in the field of palaeoclimate modelling, which can in turn bring a lot in climate model development.

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