INTEGRATING COMPONENTS OF THE EARTH SYSTEM TO MODEL GLOBAL CLIMATE CHANGES: IMPLICATIONS FOR THE SIMULATION OF THE CLIMATE OF THE NEXT MILLION YEARS

J.-C. Duplessy
Laboratoire mixte CEA-CNRS-UVSQ, France

The climate system is complex because it is made up of several components (atmosphere, ocean, sea ice, continental surface, ice sheets), each of which has its own response time. The paleoclimate record provides ample evidence that these components interact nonlinearly with each other and also with global biogeochemical cycles, which drive greenhouse gas concentration in the atmosphere. Forecasting the evolution of future climate is therefore an extremely complex problem. In addition, since the nineteenth century, human activities are releasing great quantities of greenhouse gases (CO_2, CH_4, CFC, etc.) into the atmosphere. As a consequence, the atmospheric content of these gases has tremendously increased. As they have a strong greenhouse effect, their concentration is now large enough to perturb the natural evolution of the earth's climate.

In this paper, we shall review the strategy which has been used to develop and validate tools that would allow to simulate the future long-term behaviour of the Earth's climate. This strategy rests on two complementary approaches: developing numerical models of the climate system and validating them by comparing their output with present-day meteorological data and paleoclimatic reconstructions. We shall then evaluate the methods available to simulate climate at the regional scale and the major uncertainties that must be solved to reasonable estimate the long-term evolution of a region, which would receive a geological repository for nuclear wastes.

Modelling the general circulation of the atmosphere

It was realised as early as the Mid twentieth century that modelling the global climate system was the only approach allowing to forecast the long-term ($\sim 10^6$ years) evolution of the earth's climate. However, this was at that time an impossible task due to the difficulty to account for the physics of the energy exchanges between atmosphere, ocean, sea-ice, land surface and ice sheets. It was thus necessary to simplify the problem and first focus on the dominant component of the system, the atmosphere. Indeed, climate is made by the general circulation of the atmosphere i.e. the global pattern of air movements, with air masses rising at low latitude to descend farther north, trade winds in the intertropical zone, cyclonic storms that carry energy and moisture through middle latitudes, etc. Following Bjerknes ideas, Atmospheric General Circulation Models (AGCMs) were built to numerically solve a set of "primitive equations" describing the behaviour of heat, air motion, and moisture. The solution of these equations would describe and predict large-scale atmospheric motions.

Three-dimensional AGCMs discretise the equations for fluid motion and integrate them forward in time. To do the computations within a reasonable time, models had to use a grid with cells about a thousand kilometers square, averaging over all the details of weather. The smallest single cell in a global model that a computer can handle is far larger than an individual cloud. Thus the computer calculates none of the cloud's details. Models therefore contain parametrisations for processes – such as convection, evaporation of moisture from the soil, reflection from ice – that occur on scales too small to be resolved directly. Parameterisations are just a set of parameters that represent in a simplified way the net behaviour of these processes in a cell under given conditions.

A first step is to validate models by checking their ability to simulate the present day climate. However, as parameterisations are rather crude and often tuned to get a realistic modern climate, other validations are necessary. A second step is therefore to validate the models by checking their ability to simulate past climates without changing any parameterisation. However, to simulate a glacial climate with an AGCM, a lot of boundary conditions were different from those of today and should be known, noticeably insolation, geography, sea level, ice sheet extension and altitude, continental vegetation and albedo and sea surface temperature (SST). Such boundary conditions were provided by the results of the CLIMAP Project. They combined SST estimates derived from fossil fauna in deep sea sediments with terrestrial data from fossil pollen to generate a world map of surface conditions at the peak of the last ice age. The first attempts showed only a very rough agreement, although good enough to reproduce essential features such as the important role played by the reflection of sunlight from ice, the aridity of the topics, the weak summer monsoon, the strong winter monsoon and a cooling of high latitudes much greater than that of low latitudes.

Modelling the general circulation of the ocean

Numerous experiments in which only SSTs were changed in a few oceanic grid cells demonstrated that the simulated climate closely depends from the oceanic boundary conditions imposed to the AGCM. Modelling the oceanic circulation was therefore necessary and oceanographers developed ocean GCM (OGCM). These numerical models aim to simulate the global ocean circulation when forced by atmospheric heat and momentum fluxes. The same validation strategy was applied, first the simulation of the modern circulation and second the simulation of the glacial ocean circulation. In this latter case, boundary conditions different from those of today were a pre-requisite. They were provided by the CLIMAP SST, surface salinity estimates derived from the isotopic composition of planktonic foraminifera and wind fields computed by an AGCM forced by glacial boundary conditions reconstructed during the CLIMAP project. These models demonstrated their ability to simulate the present-day wind-driven and thermohaline circulations and the large changes in thermohaline circulation which occurred during the last glacial maximum.

In addition, sensitivity experiments with changing surface salinity in the North Atlantic have explained some cooling and circulation changes associated with massive iceberg discharges, which occurred during the last glaciation. Unlike the glacial-interglacial changes, these rapid climatic shifts are not associated with variations in the orbital parameters of the Earth and must be explained by internal reorganisation of the climatic system. Major icebergs discharges are a consequence of instabilities of the continental ice sheets. They have punctuated the last glacial period and resulted in a large injection of freshwater reducing the salinity and the density of surface water. Surface hydrological changes induced a drastic reduction of deep water formation in the Nordic Seas and a slowdown of the overall Atlantic thermohaline circulation. OGCM showed that the decreased advection of heat carried from the Southern Hemisphere by oceanic circulation explained the cooling of the North Atlantic area. At the end of the iceberg discharge, a rapid restart of the circulation leads to abrupt warming. These results provided the first evidence of the small stability of the thermohaline circulation and its sensitivity to a minor reduction of the surface water salinity/density in the Nordic Seas.

Coupled models of the climate system

AGCM and OGCM alone may thus be used to simulate mean stable conditions, for instance the climate of the present interglacial or that of the LGM or the impact on the ocean circulation of a permanently reduced surface salinity in high latitudes. They do not simulate the behaviour of the climate system in function of time. If transient climate changes were to be simulated, it was essential to construct a realistic model of the joint ocean-atmosphere system. To do so, an AGCM and an OGCM are fully coupled in a way that winds and rain computed by the AGCM would drive the ocean currents, while SST and evaporation from the sea computed by the OGCM would drive the atmospheric circulation of the AGCM. These coupled AOGCM have been successful in roughly simulating both present-day and glacial climates.

More interestingly, they also were able to simulate a climate change, such as the inception of a glaciation. The mechanism by which seasonal and latitudinal variations of the incident solar radiation initiate internal feedbacks that produce a shift from an interglacial to a glacial mode are not fully understood. Khodri et al. forced the IPSL-CM2 ocean-atmosphere coupled model with the 115 000 ky BP insolation parameters and compared a 100-year-long sensitivity experiment with a control experiment for modern conditions. The insolation changes lead to a winter surface warming and a summer cooling over the Northern Hemisphere. The thermohaline circulation is also affected, with less active winter convection in the Norwegian-Greenland Sea, as a consequence of both warmer winter conditions and enhanced atmospheric moisture transport resulting in an increase of the Siberian river runoff into the Arctic and lower salinity of the Nordic seas. The enhanced high latitude cooling of the Northern hemisphere, together with the increased atmospheric moisture transport, provides optimal conditions for delivering snow over the northern high latitude continents. The model also simulates the sudden development of perennial snow cover over the Canadian archipelagos and northern Fennoscandia, which are both thought to be the nucleation sites of the ice sheets of the last glacial period. It should be pointed out that, in this experiment, the growth rate of the snow cover is far smaller than that required to develop an ice sheet at the rate of about five millions of km^3/kyr, as suggested by geological data. One feedback was missing. The model simulation did not consider biosphere-atmosphere interactions, which would lead to further cooling: the replacement of the boreal forest by tundra would enhance the surface albedo of high latitudes, thus favouring the onset of glaciation. A more realistic ice sheet growth rate is simulated when the OAGCM is coupled to an interactive vegetation model.

Earth model of intermediate complexity

Paleoclimatic reconstructions and their modelling illustrate the fact that climate primarily changes as a result of long-term insolation variations, but that the mechanism of these variations results from an intricate set of complex interactions. As a consequence, a reasonable forecast of future climate requires to run models able to simulate the interactions between ocean, atmosphere, continental vegetation, ice sheets and biogeochemical cycles.

To do the computations with AOGCM within a reasonable time, models had to use a grid with cells several thousands kilometers square, averaging over all the details of weather, and the present-day computer power allows to simulate the transient behaviour of the climate for no more than a few centuries. In order to represent the continuous long-term climate evolution over hundreds of millennia, all the components of the climate system must be represented in a simplified way when compared with detailed state-of-the art models. The resulting models are called Earth system models of intermediate complexity (EMIC). The advantage of this approach is to reduce the computing time required for long simulations while explicitly taking into account the transient interactions between the different components of the climate system. In this way, the main feedback mechanisms and their relative importance in the long-term evolution of climate can be identified and quantified through sensitivity studies.

As usual, EMICs have been validated on both modern and past climates. As modern computers allow to perform numerous simulations within a short time span (1 year of model climate is computed in a few minutes), EMICs can be used either to simulate hundreds of millennia of natural climate evolution or to perform numerous transient experiments in order to determine parameters which provide the better fit with geological data. As an example, the CLIMBER-2 climate model of intermediate complexity, in which the water isotopes have been implemented, has been used to compute a classic paleoceanographic tool, the oxygen isotope composition of planktonic foraminifera which have lived during one of the most massive iceberg discharge of the last glaciation. Numerous simulations were performed with different duration and flux of freshwater discharge. Results were compared with geological data and a maximum in the computed similarity was determined for a flux-duration of 100-400 yr and an annual injection of 0.24-0.34 Sv (1 Sv = 10^6 m^3/s). The model compute the water input to be ~2 m of equivalent sea-level, the simulated temperature anomaly to be 6-8°C at 45°N and a drastic reduction of the thermohaline circulation during the first 150 years. A relatively minor perturbation of the hydrological cycle had thus a large impact on the ocean circulation and the whole climate system.

Regional climate simulations and downscaling

Obviously, the grid of EMICs has very large cells, sometimes $>10^5$ km^2. Consequently, in order to get a quite realistic-looking climate at the scale of a region, as it is required to forecast the long-term evolution around a geological repository, special methodologies have to be developed. A first approach is to use a regional model which will be forced by the EMIC output and compute climatic conditions over a region like Europe with a resolution of about 50 km × 50 km. These models have a very detailed physics, a good representation of orography and can be tested by meteorological observations provided by weather services. They allow to numerically estimate surface temperature, rainfall, snowfall and winds for the different seasons at the regional scale. A second, very different approach, called downscaling, uses climatological statistics calculated from modern data to derive regional temperatures and precipitations from the low-resolution simulations performed with EMICs. The basic predictors are the distance to the sea (continentality index) and the surface elevation relative to sea level. For a given month, they jointly explain more than 90% of the variance of the temperature field and about 60% for the precipitation. A test performed with LGM conditions show that the downscaling method provides significantly different results from those derived from the simple output of the GCM, noticeably in areas affected by coastline changes such England. The continentality effect is better taken into account. However, the surface air temperature simulations (with and without downscaling) do not depict cooling as large as those suggested by pollen data over most of Europe. Clearly there are a lot of improvements to bring to this new approach, noticeably in the treatment of seasonality, which might experience tremendous changes under climate conditions different from those of today.

Greenhouse gases and impact of human activities

Greenhouses gases constitute a strong feedback to natural climate changes triggered by insolation variations. For instance, GCM simulations suggest that the low atmospheric CO_2 content during the glaciation account for about one third of the LGM global cooling. Before the industrial era, the atmospheric CO_2 content was close to 280 ppm. It has sharply increased since 1 850 AD and is now close to 380 ppm, a value that has never been reached during the last million years. With the expected growth of the world population and energy requirements for the next centuries, more and more fossil fuel will be consumed and CO_2 injected into the atmosphere. Future atmospheric CO_2 concentration will mainly depend on the amount of fossil fuel burnt during the next centuries and on the rate at which the other components of the carbon cycle (ocean, vegetation, chemical erosion) will absorb the anthropogenic CO_2. However, these chemical reactions have very different time constants and efficiencies in reducing the atmospheric CO_2 content. First, equilibration with sea water on a time scale less than a millennium would damp by ~20-30% the transient peak in atmospheric pCO_2. Second, acidifying the ocean perturbs the carbonate cycle and carbonate dissolution will tend to restore the pH of the ocean to its pre-industrial value, on a time scale of ~10 000 yr, but atmospheric pCO_2 will remain significantly higher than pre-industrial values. Third, silicate weathering with a time constant of a few 10^5 years will be the ultimate sink. Due to its long time constant, the atmospheric pCO_2 will still be higher than the pre-industrial value after 10^5 years. All these processes are still poorly known and the evolution of atmospheric pCO_2 is only known with large uncertainty. How the major processes driving the natural carbon cycle will be affected is still unknown.

Such long-term memory of human activities by the atmosphere has major implications for future climates. Model simulations performed with EMICs show that a glaciation can be initiated when the summer insolation of Northern Hemisphere high latitude falls below some threshold, which depends on atmospheric pCO_2. Future glaciation may well be prohibited until most of the anthropogenic CO_2 be pumped away by erosion and atmospheric pCO_2 falls below some threshold. Forecasting the magnitude of this effect is more difficult than estimating the trigger insolation at natural interglacial pCO_2 levels, because future climates will be different from the present and we have no well-documented analog in the paleoclimate record. Although the differ by their response to the same pCO2 scenarios and insolation forcing, simulations performed with different EMICs all show that the present interglacial may last for several 10^5 years and that the natural evolution of the climate will remain perturbed by anthropogenic CO_2 during most of the next million years.

Conclusion

While the progress in climate science has provided much better tools to simulate the past and future evolution of the climate system, its complexity and the multiple interactions that determine its behaviour impose limitations on our ability to predict fully the future course of Earth's climate. There is still an incomplete physical understanding of many components of the climate system and their role in climate change.

Climate models are the primary tool used for understanding and attribution of past climate variations, and for future projections. They are now able to simulate the gross trends of Quaternary climates (mainly ice volume variations) and provide reasonable forecasts of what would have been the ice volume variations during the next million years under purely natural conditions, i.e. without significant impact of human activities. Efficient approaches are being developed to simulate climatic conditions at the regional scale.

However, the future of the earth's climate will not be determined by only natural conditions. We have now ample evidence that anthropogenic CO_2 release perturbs the present climate and will continue to affect it in the future. There are no historical perturbations to radiative forcing that are fully analogous to the perturbations expected over the next centuries and confidence in the models must be built from a number of indirect methods. The ability of climate models to provide a physically self-consistent explanation of past climate variations on geological timescales builds confidence that the models are capturing many key processes for the climatic evolution of the next centuries.

Surprisingly, the long-term variations of atmospheric CO_2 concentration for a given emission scenario are poorly known and we still do not know how long they will remain higher than the threshold value permitting the growth of continental ice sheets over the Northern hemisphere and a glacial climate. As glacial-interglacial oscillations are the main factor driving climate and environment changes over Europe, the degree of human perturbation of the global carbon cycle is now a key uncertainty in forecasting the evolution of the environment around a geological repository.