A climate model reflecting the complexity of the earth system

William W. Hay

GEOMAR, Kiel

Introduction

Atmospheric General Circulation Models (AGCMs) do well at simulating conditions within the atmosphere, but geologic deposits form at the surface of the solid earth directly beneath the atmosphere or water. The best test of a climate simulation is how well it predicts conditions at the land surface. Further, the scale of atmospheric circulation is such that a spatial resolution of 500 km is generally adequate to describe its motions. Climate sensitive geologic deposits rarely extend over such large distances without change.

After a number of years working with colleagues at U. S. National Center for Atmospheric Research (NCAR) and attempting to simulate the climate of the Cretaceous with the NCAR Community Climate Model (CCM), Bill Hay concluded that it was inadequate and not suitable for understanding the very different climates of the Earth's past. The CCM derives its name from the fact that it was built of many components contributed by members of the atmospheric science community. The NCAR CCMs have done well at simulating conditions within the atmosphere. Snow, sea-ice, soil, a surface ocean, and vegetation have been incorporated in newer versions of the CCM. In spite of their sophistication, the results of the CCM simulations for paleoclimate were disappointing. Twenty years of experiments were unable to produce a realistic description of conditions during the Cretaceous (Barron, 1981, 1983, 1984, 1985; Barron and Washington, 1982a, b, 1984, 1985; Barron et al., 1985, 1991, 1992, 1993; Schneider et al., 1985; Glancey et al., 1986; Oglesby and Park, 1989, 1992; Sloan and Barron, 1990; Park and Oglesby, 1990, 1991; Barron and Moore, 1994).

Paleoclimate models pose a number of special problems. Not only must the continents and terranes be in their ancient positions, but the shoreline and paleotopography must be specified. Lakes and swamps are important as sources of moisture in the continental interiors and need to be included in the paleogeography. Soils and vegetation are important to the hydrologic cycle, but there are special problems associated with them because vegetation has changed with time, and information on ancient soils is scarce. Groundwater is important as a source of water in rivers and may influence vegetation. Ice sheets are large topographic features that may influence atmospheric circulation; the ice moves and may extend beyond the positions that a model would predict for perannial snow.

Paleoclimate simulations can be tested by proxy formation models designed to determine whether climate sensitive sediments might have been deposited at a specific location if conditions at the land or sea surface are precisely known. Proxy formation models also have the potential to explore conditions at different elevations and environments within the land surface grid cells.

The only test commonly applied to AGCMs is whether they can reproduce the present climate. Paleoclimate simulations can be tested against geologic observations. They can test the ability of climate models to predict conditions under significantly altered boundary conditions.

To remedy the lack of a model suitable

for paleoclimate simulation, Starley Thompson of NCAR and Bill Hay, then at the University of Colorado, obtained a grant from the Earth Sciences Section of the U. S. National Science Foundation to produce a model specifically designed to simulate climates of the Earth's past. The grant provided funding for a highly skilled programmer, David Pollard, to rewrite the CCM code and fix its limitations. It was intended that the model be able to handle paleogeographies, atmospheric conditions, vegetation cover, and soils very different from today. The result was GENESIS (Global Environmental Ecological Simulation of Interactive Systems), a climate-oriented Earth System Model (Fig. 1). GENESIS reproduces present conditions well (Pollard and Thompson, 1995, 1997; Thompson and Pollard, 1995a, b, 1997). The initial tests of the new model were simulations of Triassic climate (Hay et al., 1994; Wilson et al., 1994).

A realistic simulation of the Cretaceous climate

GENESIS produced the first realistic simulation of the Cretaceous climate in Spring 1996 (DeConto, 1996; Hay et al. 1997; DeConto et al. 1998, 1999, 2000). The Cretaceous meridional temperature is duplicated, the continental interiors remain close to freezing in the winter, and conditions are compatible with the distribution of all climate indicator deposits (Hay et al., 1997). The simulation correctly predicts the distribution of evaporites and coals and correctly describes the structure of plant communities at high latitudes.

The new simulation used boundary conditions similar those of prior studies, with a solar constant equal to 99 % present, mean orbital parameters, four times present atmospheric CO_2, and

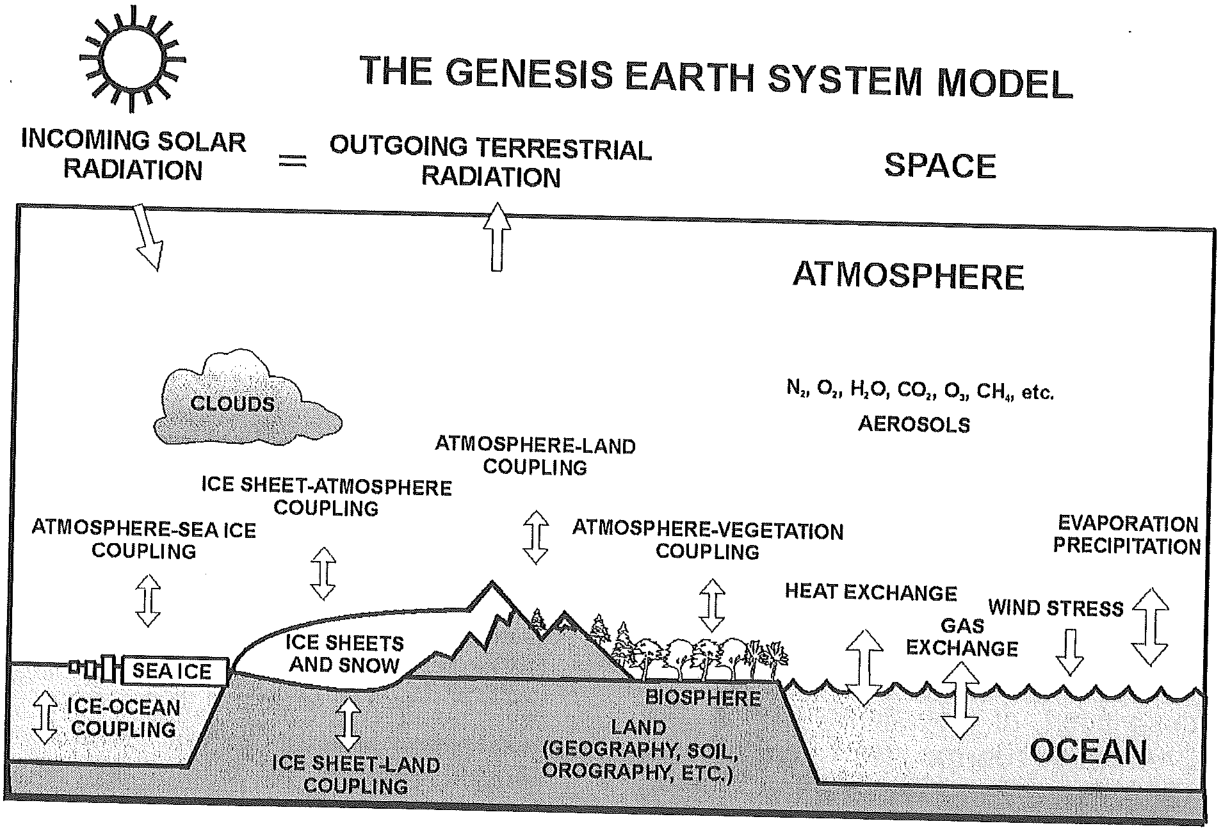

Fig. 1: The GENESIS Earth System Model representation of the climate, showing the major processes and interactions between parts of the systems.

ocean heat transport equal to that at present.

The success of the new simulation depended on new model components that describe parts of the climate system usually generalized or neglected: 1) detailed paleogeography and paleotopography, 2) a soil model with different rates of infiltration of water into six layers of soil and into the groundwater system, and 3) a vegetation model that interacts with the climate model to produce new vegetation each model year until the vegetation and climate are in equilibrium. Success came only after the evolutionary history of plants was taken into account. The C4 plants, such as grasses, which were not widespread in the Mesozoic, were replaced by herbaceous C3 plants in the vegetation model. The change in physiology from C3 to C4 plants has altered the transpiration rate and atmospheric vapor content enough to cause significant deterioration of the climate in the continental interiors. The Cretaceous simulation suggests an overall global mean temperature about 4°C higher than today, with a much greater role for water vapor in transporting latent heat through the atmosphere. Surface ocean temperatures and salinities predicted by the model are shown in Figure 2.

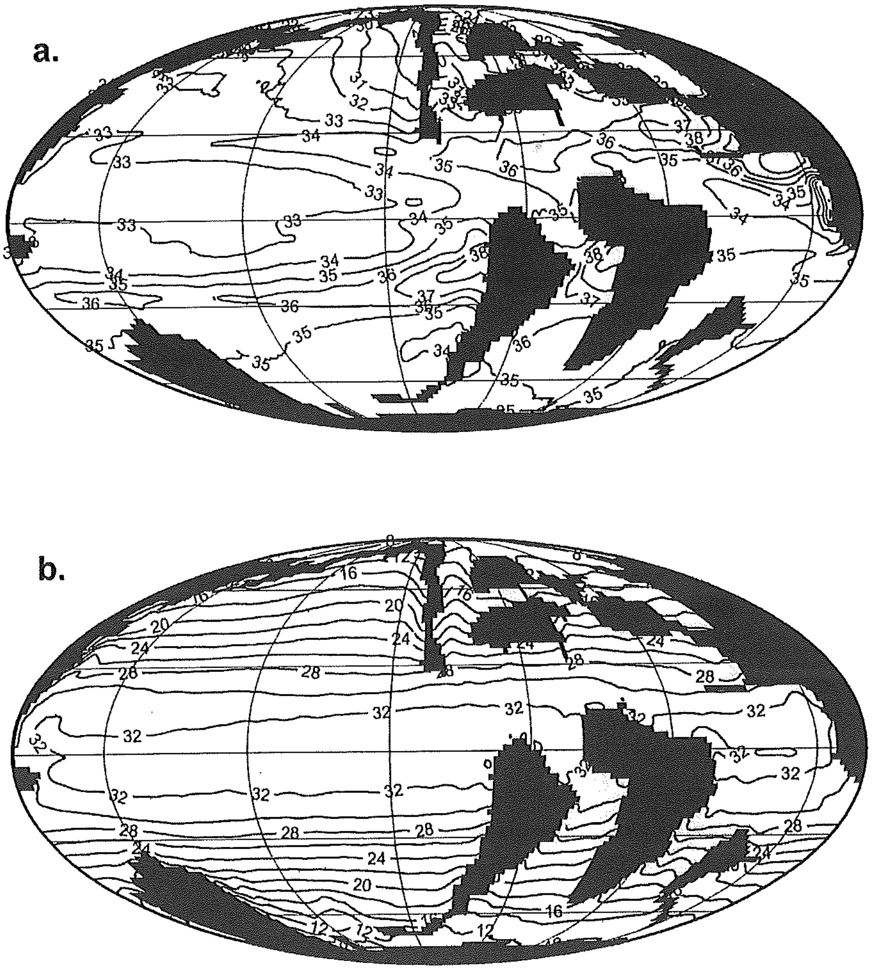

Fig. 2: Salinity (a) and temperature (b) of the sea surface in the Campanian after a GENESIS paleoclimate simulation by DeConto et al. (1996).

The GENESIS Earth System Model

GENESIS is a modular Earth System Model with an Atmospheric General Circulation Model (AGCM) coupled to a 50 m mixed layer slab ocean model as its core component and includes multi-layer models of snow, sea-ice, and soil, and an interactive biosphere model (Fig. 3). Proxy formation models test the simulations.

The GENESIS *ACGM* component is a heavily modified version of NCAR's CCM1, described in Williamson et al. (1987). The code was extensively modified to include new model physics and global arrays. The solar radiation scheme include a diurnal cycle with solar radiation calculations performed every 1.5 model hours for all atmospheric layers. Atmospheric convection and planetary boundary layer mixing is simulated using an explicit sub-grid scale plume model (Anthes, 1977). Atmospheric dynamics include gravity-wave drag (McFarlane, 1987) and dynamic Courant spectral truncation in the upper stratosphere.

The radiative effects of *greenhouse gasses*, H_2O, CO_2, CH_4, N_2O, O_3 and CFCs are treated explicitly. The radiative effects of tropospheric aerosols can also be included. The model can treat conditions in which ash or smoke completely block out the sun (Thompson et al., 1987). Water vapor is advected in grid space by a semi-Lagrangian transport, as described in Williamson and Rausch (1989), Rausch and Williamson (1990) and Williamson (1990).

Clouds are especially important because

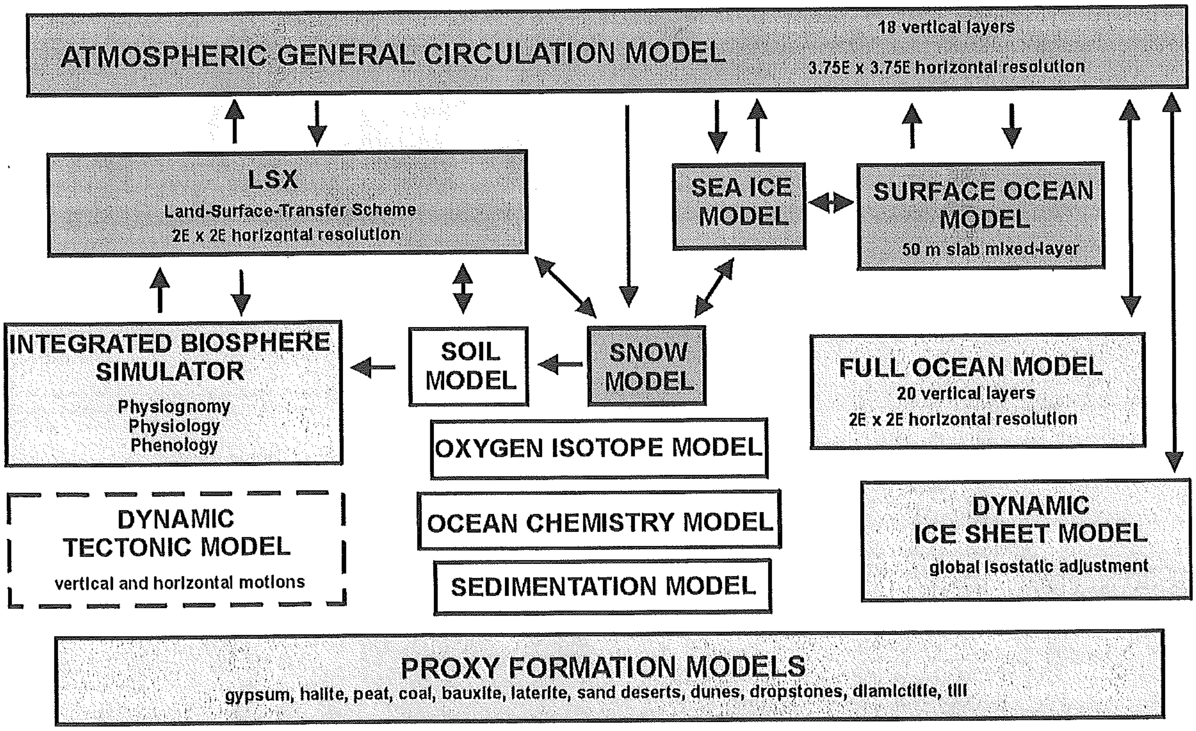

Fig. 3: The primary components of the GENESIS Earth System Model. Bi-directional arrows indicate communication between individual model components, allowing feedback mechanisms to operate in realistic ways. LSX serves as the interface between land surface sub-models (Biosphere, Soils, Snow) and the AGCM. The surface ocean and sea ice models communicate directly with the AGCM. The results of the AGCM simulation can be used to drive a full ocean model. The degree of shadding indicates that the model is not likely to be greatly improved. Modules in dashed rectangles have not been developed beyond the conceptual stage.

they are responsible for most of the reflectivity of the Earth at present. They are also very important to the radiation budget because water droplets absorb infrared radiation at all wavelengths. The GENESIS cloud parameterization is similar to Slingo & Slingo (1991), and uses three types of clouds: stratus, anvil cirrus, and convective. Multi-layer, randomly overlapping clouds are included in the solar radiation calculations.

The resolution of a climate model is a function of the *grid scale* used for calculations. The AGCM uses a nearly equispaced gaussian latitude grid (Washington and Parkinson, 1986). Resolution in the Triassic simulations was “R15" (4.75° latitude and longitude) with 12 vertical levels. The AGCM now uses a spectral horizontal T31 grid (3.75° latitude and longitude) and 18 vertical levels; 3 of the 6 new vertical levels are in the planetary boundary layer. To generate geologically relevant data GENESIS uses an equispaced surface grid with a resolution of 2° x 2° to describe conditions at the land, ocean and lake surfaces. This approximates the limit of precision for location of points on the Earth's surface for pre-Pliocene geographies. The surface grid is used by the Land Surface Transfer Scheme (LSX), soil, snow, sea-ice, and slab ocean models. The AGCM and surface grids are independent; fields are transferred between them by interpolation (AGCM to surface) or area-averaging (surface to AGCM).

The *Land Surface Transfer Scheme (LSX)* is the interface between the atmosphere and land surface, including the vegetation. It is based on the earlier BATS (Biosphere-Atmosphere Transfer Scheme; Dickinson et al., 1986) and SiB (Simple Biosphere model; Sellers et al., 1986) models. It computes the exchanges of momentum, thermal energy, and water between the atmosphere and the land surface, accounting for the physical effects of vegetation, soil texture, and snow cover. Two vegetation layers or canopies, such as “trees” and “grass,” can be specified at each grid point. The LSX calculates the radiative and turbulent fluxes through these layers to the soil or snow surface. Rain or snow intercepted by the vegetation eventually drips or blows off. Given the AGCM conditions above the upper canopy and the soil or snow conditions below, the LSX predicts vegetation temperatures and canopy air temperatures and specific humidities. Prognostic fields are then passed back to the AGCM, allowing interaction between the Earth's surface and atmosphere. The two vegetation canopy heights, leaf area index, fractional cover, leaf albedo, and leaf orientation are defined by the vegetation type specified at each surface grid point.

For the *vegetation*, the Cretaceous simulation used the Equilibrium Vegetation Ecology (EVE) model developed by Bergengren et al. (submitted). EVE predicts plant community structure as a function of temperature, precipitation, relative humidity, and fundamental ecological principles. It was run interactively with the AGCM; the climatic information drives EVE, and EVE provides vegetation boundary conditions for the land surface. More recently an Integrated Biosphere Simulator (IBIS) has been developed by Jon Foley at the University of Wisconsin (Foley et al., 1996). It integrates land surface processes, terrestrial carbon balance, and vegetation dynamics. It describes winter- and drought-deciduous plant behavior, follows the carbon balance of gross photosynthesis, respiration, and growth for nine plant functional types, and simulates changes in vegetation cover, primary productivity, carbon allocation, biomass growth, mortality, and biomass turnover for each plant type. Competition for sunlight and soil moisture determines the distribution of plant functional types, the relative dominance of trees and herbaceous plants, evergreen and deciduous phenologies, broadleaf and conifer leaf forms and photosynthetic pathways.

The *soil model* has six layers and extends to a depth of 4.25 m. Heat is diffused linearly and moisture nonlinearly, according to soil texture (Clapp and Hornberger, 1986). Soil moisture is removed from rooted soil layers according to transpiration rate. Ice within the soil is predicted, and the latent heat of fusion and amounts of ice and liquid water are accounted for explicitly. Surface runoff and subsurface gravitational drainage are allowed to occur if precipitation minus evaporation exceeds the infiltration rate. Combined runoff and drainage is globally integrated and transferred uniformly to the ocean at each time step. Stochastic precipitation is supplied by single-point LSX values. Surface ponding of water occurs at grid points where the precipitation rate exceeds the infiltration rate. The model also includes an explicit litter layer, nonlocal downward transport through near-surface microscopic channels, and hydrostatic pressure in saturated soil columns.

The *snow model* has three layers in the snow cover on soil, ice sheet, and sea-ice surfaces. Snow thickness is changed according to accumulation and melting rates on the uppermost layer. Fractional snow cover is accounted for. Snow moisture content, percolation, and refreezing are modeled after Loth et al. (1993).

Sea-ice is treated by a six-layer thermodynamic model predicting the local melting and freezing of ice, following Semtner (1976). Heat is diffused linearly through the ice. Ice thickness is controlled by melting or freezing of the top and bottom layers.

A slab ocean model is used with the AGCM. the ocean is represented by a 50 m thermodynamic slab that captures the seasonal thermal capacity of the mixed layer. Poleward oceanic heat flux is defined as a linear diffusion down the local temperature gradient, according to a zonally symmetric function of latitude based on present day observations (Covey and Thompson, 1989) and the zonal fraction of land and sea at a given latitude.

Proxy formation models (PFMs) have been or are being developed to predict the potential for occurrence of evaporites, peat or coal, bauxite, laterite, sand deserts and dunes, and the deposits of coastal sea ice, mountain glaciers, and ice sheets. Once the climate simulation has been verified using proxy formation models, the surface climate can be used to drive an ocean model. The PFM prescribes boundary conditions that must have existed at the location where the deposits occur. This additional "grid point" is inserted into the climate model, and the calculated environmental parameters such as temperature, humidity, and rainfall are then compared with conditions required for formation of the deposit.

The GENESIS prototype *ocean model* is a version of that developed by Semtner and Chervin (1992). It has a horizontal resolution of 2° x 2°, and 20 vertical levels, and is capable of representing the major current systems but not mesoscale eddies.

Improvements in the Earth System Model needed for paleoclimate simulations

The greatest potentials for improvement lie in the addition of a dynamic glacial ice model, which is currently being developed by David Pollard at the Earth System Science Center of The Pennsylvania State University, and an interactive soil model. The ice model is important because of the significant topography and albedo of ice sheets. The flowing ice may extend beyond the area where snow would persist through the summer.

The hydrology of the present soil module is quite sophisticated, but very little is known about the distribution of ancient soils. Soils store water, and moderate the hydrologic cycle both directly and through the vegetation they support. An interactive soil development model that would start from the parent rock and then predict the type and properties of soil in equilibrium with the climate and vegetation would be a major improvement. This would require three-way iterations between the climate, vegetation, and soil models.

Finally, the possibility for changing boundary conditions should be built into the Earth System Model. It is now possible to change parameters such as greenhouse gas concentrations in a climate model while it is running, and so to change the simulation before or even after equilibrium is reached. Changing the geologic boundary conditions, such as the topography, would allow climate models to be used to determine whether there are paleogeographic thresholds that cause the climate to change form one state to another.

Availability and Requirements

GENESIS is available at no cost from David Pollard at The Pennsylvania State University. Earlier versions have been distributed to several institutions in the U.S and have been used extensively for paleoclimate studies. Although it originally required a very large Cray computer to run, it has been modified by Pollard so that it will now run on smaller Crays and on multiprocessor Sun Microsystems computers. A new paleoclimate simulation requires about one month of computing time.

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