Table of EMICs

(Earth System Models of Intermediate Complexity)

Edited by
Martin Claussen
Potsdam Institute for Climate Impact Research
(e-mail: claussen@pik-potsdam.de)

last update: August 2000; **http://www.pik-potsdam.de/data/emic/table_of_emics.pdf**

Introduction

At the IGBP (International Geosphere-Biosphere Programme) workshop held in Potsdam, Germany, on June 15-16, 1999, the state of the art of modelling the natural Earth system was reviewed. It became apparent that Earth system modelling has to rely on a hierarchy of models in which models of intermediate complexity can play a central role. Depending on the nature of questions asked and the pertinent time scales, there are, on the one extreme, conceptual, more inductive models, and, on the other extreme, three-dimensional comprehensive models operating at the highest spatial and temporal resolution currently feasible. Models of intermediate complexity bridge the gap. The so-called EMICs describe most of the processes implicit in the comprehensive models, albeit in a more reduced, i.e., more parameterized form. They nevertheless simulate the interactions among several, or even all components of the Earth system explicitly. On the other hand, EMICs are simple enough to allow for long-term simulations over several 10,000 years or a broad range of sensitivity experiments.

Up to now, there is no concise definition of an EMICs. Perhaps, this will presumably never be achieved, because the border between EMICs and comprehensive models will change with time and computer capacitiy. Therefore, in a follow-up workshop in Nice, in April 2000, it was decided to publish a table of EMICs which are currently in operation. This table should reflect the broad spectrum of EMICs; moreover, it should provide an overview what EMICs can do and where their limitations are. We hope that it will became apparent that EMICs are not designed to compete with comprehensive models, but to complement them. In severals cases, EMICs can provide just some guidance for a more thorough investigation using comprehensive models, but there are many problems in Earth system modelling which can be tackled by EMICs only.

This table is produced by the principal investigators, and the principal investigators are responsible for the description of their models. The table will be updated regularly.

(Thanks are due to Johann Grüneweg, PIK, for editorial assistance.)

Content

The Bern 2.5D climate model

version May 2000

Principal Investigators

T. F. Stocker (stocker@climate.unibe.ch)
F. Joos (joos@climate.unibe.ch)
O. Marchal (marchal@climate.unibe.ch)

University of Bern
Climate and Environmental Physics
Sidlerstr. 5
CH-3012 Bern
Switzerland

A Scope of the model

The Bern 2.5D Climate Model is designed to study the role of the large-scale ocean thermohaline circulation in the Earth climate system of the past, present and future. We focus on the stability and dynamics of the thermohaline circulation and its interactions with the ocean carbon cycle on timescales of more than several decades and on spatial scales of more than a thousand kilometers. The simple parameterization of processes results in a computationally efficient climate model suitable for long-term integrations (up to millions of years) and large numbers of simulations not feasible with more complex models. This allows us to focus in detail on the mechanisms and processes of natural climate variability and on the potential anthropogenic climate change.

B Model components

- Energy balance model of the atmosphere with 'active' hydrological cycle
- Zonally averaged ocean model
- Thermodynamic sea ice model
- Ocean carbon cycle model
- Four-box terrestrial biosphere model

Atmosphere

- Balance for heat and freshwater, no dynamics [Stocker et al., 1992a]
- Evaporation parameterized, precipitation determined from evaporation and meridional fluxes of sensible and latent heat, no freshwater storage in the atmosphere
- Active hydrological cycle [Schmittner and Stocker, 1999; Schmittner et al., 2000a]. Meridional transport of sensible and latent heat parameterized as Fickian diffusion with latitude-dependent eddy diffusion coefficient.
- Resolution: 17 meridional cells, zonally and vertically averaged. Meridional resolution as in the ocean.
- No flux corrections required

Ocean

- Dynamics based on vorticity conservation [Wright and Stocker, 1991; Stocker and Wright, 1991b]
- Different closures schemes (parameterization of the zonal pressure gradient) [Wright et al., 1995; Wright et al., 1998]
- Three zonally averaged basins, connected through the Southern Ocean south of 47.5°S, meridional resolution 7.5° to 15°, 14 vertical layers, flat bottom
- Different subgrid-scale mixing parameterizations [Knutti et al., 2000]

Sea ice model

- Simplest version of the thermodynamic sea ice model of Semtner [1976], no advection of sea ice

Ocean carbon cycle

- Description of the cycles of organic carbon and $CaCO_3$ [Marchal et al., 1998b], based on Redfield approach using PO_4 as biolimiting nutrient. Production of organic carbon exported from the euphotic zone is related to the local PO_4 availability via Michaelis-Menten kinetics. Export production partitioned between POC and DOC and recycled below euphotic zone. Tracers: DIC, DOC, ^{13}C and ^{14}C in DIC and DOC, Alkalinity, PO_4, O_2.

Terrestrial biosphere

- 4-box terrestrial biosphere (Ground, Wood, Detritus and Humus) [Siegenthaler and Oeschger, 1987]. A potential fertilization by elevated atmospheric CO_2 is taken into account by a logarithmic dependence of net primary production.

Miscellaneous

- Seasonal cycle implemented [Schmittner and Stocker, 2000]
- Additional tracers: Chlorofluorocarbons CFC11 and CFC12, and radionuclides ^{231}Pa and ^{230Th} [Marchal et al., 2000]

C Limitations

- Coarse resolution and zonal averaging restrict studies to spatial scales of more than a thousand kilometers and to timescales of more than several decades
- Land surface processes are poorly represented
- No ocean sediments

D Performance

- Computational efficiency: at least 20'000 yrs per CPU hour (Compaq Alpha Workstation XP1000, 500 MHz), depending on model version, biology, ocean mixing parameterization and timestep.
- Memory usage: <100 MB

E Applications

- Modelling the thermohaline circulation: Model development, sensitivities and validation [Wright and Stocker, 1991; Stocker and Wright, 1991b; Stocker et al., 1992a, Wright and Stocker, 1992; Wright et al., 1995; Wright et al., 1998; Schmittner et al., 2000a; Schmittner and Stocker, 2000]
- Dynamics of the thermohaline circulation [Stocker and Wright, 1991a; Stocker et al., 1992b, Lehman et al., 1993; Wright and Stocker, 1993; Aeberhardt et al., 2000; Knutti et al., 2000]
- Studies of the ocean carbon cycle [Stocker et al., 1994; Lynch-Stieglitz et al., 1995; Marchal et al., 1998a; Marchal et al., 1998b; Broecker et al., 1999; Joos et al., 1999; Marchal et al., 1999a, Marchal et al., 1999b, Vidal et al., 1999] and other marine tracers [Schulte et al., 1999; Marchal et al., 2000]
- The role of the thermohaline circulation in a global warming context [Stocker and Schmittner, 1997; Schmittner and Stocker, 1999; Schmittner et al., 2000b]
- Effects of ocean circulation changes on atmospheric radiocarbon [Stocker and Wright, 1996; Stocker and Wright, 1998]
- Influence of the thermohaline circulation on sea level projections [Knutti and Stocker, 2000]

F References

Aeberhardt, M., M. Blatter, and T. F. Stocker, Variability on the century time scale and regime changes in a stochastically forced, zonally-averaged ocean-atmosphere model, Geophys. Res. Let., 27, 1303-1306, 2000.

Broecker, W. S., J. Lynch-Stieglitz, D. Archer, M. Hofmann, E. Maier-Reimer, O. Marchal, T. Stocker, and N. Gruber, How strong is the Harvardton-Bear constraint?, Global Biogeochem. Cyc., 13, 817-820, 1999.

Joos, F., G.-K. Plattner, T. F. Stocker, O. Marchal, and A. Schmittner, Global warming and marine carbon cycle feedbacks on future atmospheric CO_2, Science, 284, 464-467, 1999.

Knutti, R., and T. F. Stocker, Influence of the thermohaline circulation on projected sea level rise, J. Clim., 13, 1997-2001, 2000.

Knutti, R., T. F. Stocker, and D. G. Wright, The effects of sub-grid-scale parameterizations in a zonally averaged ocean model, J. Phys. Oceanogr., (in press), 2000.

Lehman, S. J., D. G. Wright, and T. F. Stocker, Transport of freshwater into the deep ocean by the conveyor, in Ice in the Climate System, edited by W. R. Peltier, NATO ASI Ser., Ser. I, 12, pp. 187-209, 1993.

Lynch-Stieglitz, J., T. F. Stocker, W. S. Broecker, and R. G. Fairbanks, The influence of air-sea interaction on the isotopic composition of organic carbon: observations and modeling, Global Biogeochem. Cyc., 9, 653-665, 1995.

Marchal, O., R. François, T. F. Stocker, and F. Joos, Ocean thermohaline circulation and sedimentary ^{231}Pa/^{230Th} ratio, Paleoceanogr., (submitted), 2000.

Marchal, O., T. F. Stocker, and F. Joos, Impact of oceanic reorganizations on the ocean carbon cycle and atmospheric carbon dioxide content, Paleoceanogr., 13, 225-244, 1998a.

Marchal, O., T. F. Stocker, and F. Joos, A latitude-depth, circulation-biogeochemical ocean model for paleoclimate studies. Model development and sensitivities, Tellus, 50B, 290-316, 1998b.

Marchal, O., T. F. Stocker, and F. Joos, Physical and biogeochemical responses to freshwater-induced thermohaline variability in a zonally averaged ocean model, in Mechanisms of Global Climate Change at Millennial Time Scales, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, Volume 112 of Geophysical Monograph, pp. 263-284, Am. Geophys. Union, Washington, D. C., 1999a.

Marchal, O., T. F. Stocker, F. Joos, A. Indermühle, T. Blunier, and J. Tschumi, Modelling the concentration of atmospheric CO_2 during the Younger Dryas climate event, Clim. Dyn., 15, 341-354, 1999b.

Schmittner, A., C. Appenzeller, and T. F. Stocker, Validation of parameterizations for the meridional energy and moisture transport used in simple climate models, Clim. Dyn., 16, 63-77, 2000a.

Schmittner, A., C. Appenzeller, and T. F. Stocker, Enhanced Atlantic freshwater export during El Niño, Geophys. Res. Let., 27, 1163-1166, 2000b.

Schmittner, A., and T. F. Stocker, The stability of the thermohaline circulation in global warming experiments, J. Clim., 12, 1117-1133, 1999.

Schmittner, A., and T. F. Stocker, A seasonally forced ocean-atmosphere model for paleoclimate studies, J. Clim., (submitted), 2000.

Schulte, S., F. Rostek, E. Bard, J. Rullkötter, and O. Marchal, Variations of oxygen-minimum and primary productivity recorded in sediments of the Arabian Sea, Earth Planet. Sci. Lett., 173, 205-221, 1999.

Semtner, A. J., A model for the thermodynamic growth of sea ice in numerical investigations of climate, J. Phys. Oceanogr., 6, 379-389, 1976.

Siegenthaler, U., and H. Oeschger, Biospheric CO_2 emissions during the past 200 years reconstructed by convolution of ice core data, Tellus, 39B, 140-154, 1987.

Stocker, T. F., W. S. Broecker, and D. G. Wright, Carbon uptake experiments with a zonally averaged global ocean circulation model, Tellus, 46B, 103-122, 1994.

Stocker, T. F., and A. Schmittner, Influence of CO_2 emission rates on the stability of the thermohaline circulation, Nature, 388, 862-865, 1997.

Stocker, T. F., and D. G. Wright, Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes, Nature, 351, 729-732, 1991a.

Stocker, T. F., and D. G. Wright, A zonally averaged model for the thermohaline circulation. Part II: Interocean exchanges in the Pacific-Atlantic basin system, J. Phys. Oceanogr., 21, 1725-1739, 1991b.

Stocker, T. F., and D. G. Wright, Rapid changes in ocean circulation and atmospheric radiocarbon, Paleoceanogr., 11, 773-796, 1996.

Stocker, T. F., and D. G. Wright, The effect of a succession of ocean ventilation changes on radiocarbon, Radiocarbon, 40, 359-366, 1998.

Stocker, T. F., D. G. Wright, and W. S. Broecker, The influence of high-latitude surface forcing on the global thermohaline circulation, Paleoceanogr., 7, 529-541, 1992b.

Stocker, T. F., D. G. Wright, and L. A. Mysak, A zonally averaged, coupled ocean-atmosphere model for paleoclimate studies, J. Clim., 5, 773-797, 1992a.

Vidal, L., R. Schneider, O. Marchal, T. Bickert, T. F. Stocker, and G. Wefer, Link between the North and South Atlantic during the Heinrich events of the last glacial period, Clim. Dyn., 15, 909-919, 1999.

Wright, D. G., and T. F. Stocker, A zonally averaged ocean model for the thermohaline circulation, Part I: Model development and flow dynamics, J. Phys. Oceanogr., 21, 1713-1724, 1991.

Wright, D. G., and T. F. Stocker, Sensitivities of a zonally averaged global ocean circulation model, J. Geophys. Res., 97, 12,707-12,730, 1992.

Wright, D. G., and T. F. Stocker, Younger Dryas experiments, in Ice in the Climate System, edited by W. R. Peltier, Volume I 12 of NATO ASI, pp. 395-416. Springer Verlag, 1993.

Wright, D. G., T. F. Stocker, and D. Mercer, Closures used in zonally averaged ocean models, J. Phys. Oceanogr., 28, 791-804, 1998.

Wright, D. G., C. B. Vreugdenhil, and T. M. Hughes, Vorticity dynamics and zonally averaged ocean circulation models, J. Phys. Oceanogr., 25, 2141-2154, 1995.

CLIM*BER*-2

version May 2000

Principal Investigators

Andrey Ganopolski (ganopolski@pik-potsdam.de)
Vladimir Petoukhov (petukhov@pik-potsdam.de)
Victor Brovkin (brovkin@pik-potsdam.de)
Martin Claussen (claussen@pik-potsdam.de)

Potsdam Institute for Climate Impact Research
P.O. Box 60 12 03
D – 14412 Potsdam
Germany

A Scope of the model

The CLIMBER (for Climate and Biosphere) model is designed to explore the dynamic behavior of the natural Earth system, including its the feedbacks between atmosphere, ocean, vegetation, ice sheets through energy, water, momentum, and carbon cycles. Besides palaeoclimate simulations, we focus on the resilience of the natural Earth system to natural and anthropogenic perturbations such as changes in solar luminosity, historical land cover change and anthropogenic greenhouse gas emissions. In its present version, CLIMBER-2.3, is applied to long-term, ensemble simulations over several millennia (for example to the mid-Holocene – late Holocene transition) and to the simulation of glacial-interglacial cycles.
CLIMBER is described in detail in Petoukhov et al. (2000) and Claussen et al. (1999). The elements of the atmospheric module are discussed in Petoukhov and Ganopolski (1994). An extended documentation of the statistical dynamical model of the atmosphere is under preparation.

B Model components

- **POTSDAM-2**, a statistical dynamical model of the atmosphere
- **MUZON**, a zonally averaged ocean model
- **ASI**, atmosphere-surface interface
- Thermodynamic sea ice model
- Ocean carbon cycle model
- **VECODE**, a dynamic global vegetation model, including terrestrial carbon pools
- **SICOPOLIS**, a polythermal model of ice sheets
- **SEMI**, a coupler providing bidirectional interaction between atmosphere and ice sheet models

Atmosphere

- **POTSDAM-2** is a 2.5-dimensional statistical-dynamical model (Petoukhov et al., 2000). Zonal mean motion is diagnosed in terms of geostrophic and ageostrophic components. The topology of zonal mean meridional motion (Hadley, Ferrel and polar cells) is prescribed; its amplitude and horizontal extend is computed from the theory of coupled heat engines.
- Prognostic equations are set up for temperature and humidity transport on vertical average over the entire atmosphere. The vertical structure of temperature and humidity are diagnosed.
- The model calculates relative fractions in two type of clouds: large-scale stratiform and cumuli.
- Solar radiation is calculated for two subintervals (ultraviolet + visible and near infrared) using two-stream δ- Eddington method. Longwave radiation fluxes are computed on 16 atmospheric levels. Radiative schemes take into account water vapour, clouds, CO_2, aerosols, and ozone.

Ocean

- The ocean module is taken - with modifications - from Stocker, Wright and Mysak (1992). **MUZON** is a multi-basin (Pacific, Atlantic, and Indian ocean) zonally averaged model. The ocean sectors are connected via the Antarctic circumpolar current.
- No flux corrections required.

Sea ice model

- The thermodynamic sea ice model is based on an approach by Semtner (1976) being extended to include a simple description of sea-ice advection and diffusion.

- Atmosphere-surface Interface
- The CLIMBER modules, except for the ocean carbon cycle module, are coupled via surface fluxes of momentum, energy, and moisture which are computed in the module **ASI** (atmosphere-surface interface). ASI is based on the BATS scheme developed by Dickinson et al. (1986).

Ocean carbon cycle

- The ocean biogeochemistry module simulates dynamics of major biogeochemical tracers (phosphate, oxygen, dissolve inorganic and organic carbon, alkalinity,
- $\delta^{13}C$ within the ocean.
- The marine biota model by Six and Maier-Raimer (1996) is used for simulation of seasonal phyto- and zooplankton dynamics in the ocean euphotic zone.
- Vertical profiles of remineralization of organic matter and dissolution of $CaCO_3$ are calculated in accordance with approach by Yamanaka and Tajika (1996), while composition of particulate organic matter (Redfield ratio) assumed to be a function of the remineralization depth

Terrestrial biosphere

- The terrestrial vegetation module VECODE is a reduced-form dynamic global vegetation model. Vegetation is described as a fractional cover of major plant functional types (trees and grass) based on a continuous bioclimatic classification by Brovkin et al. (1997). Trees type is diagnostically subdivided into evergreen and deciduous trees.Under the forcing of climate change, the model simulates the transition of vegetation cover and carbon storage towards an equilibrium for the new climate.
- Time scale of vegetation dynamics is determined from a 4-pools model of carbon cycle.

Ice Sheets

- The model **SICOPOLIS** (Greve, 1995) is used to compute the thermodynamcis and motion of inland ice sheets.
- SICOPOLIS and POTSDAM-2 operate on rather different spatial scales; hence a special coupler **SEMI** which calculates annual mass balance of ice sheets and surface temperature at SICOPOLIS spatial grid has been constructed.

Miscellaneous

C Limitations

- Coarse resolution and zonal averaging (in the ocean model) restrict studies to spatial scales of more than a thousand kilometers and to timescales of more than several years. The model is not aimed to simulate interannual variability.

D Performance

- Computational efficiency: 12,000 yrs per CPU day with ice sheet dynamics, and 20,000 yrs per CPU day without ice sheet dynamics (IBM Workstation RS/6000).
- Memory usage: 150 MB

E Applications

- Sensitivity studies (2xCO_2, deforestation, solar variability, North Atlantic deep water formation) and comparison with GCMs (Ganopolski et al. 2000).
- The role of the ocean during the Last Glacial Maximum (Ganopolski et al. 1998a)
- Atmosphere-ocean-vegetation interaction during the Holocene, Eemian (Ganopolski et al. 1998b, Claussen et al. 1999b, Kubatzki et al. 2000)
- Historical deforestation (Brovkin et al. 1999) Dynamics of the thermohaline circulation in a global warming context (Rahmstorf and Ganopolski, 1999)

F References

Brovkin, V., Ganopolski, A., Svirezhev, Y., 1997: A continuous climate-vegetation classification for use in climate biosphere studies. Eco. Model., 101, 251-261.

Brovkin V., Ganopolski, A., Claussen, M., Kubatzki, C., Petoukhov, V., 1999: Modelling climate response to changes in land use. Global Ecology and Biogeography, 8(6), 509-517.

Brovkin, V., Ganopolski, A., Svirezhev, Yu., Claussen, M., von Bloh, W., Bondeau, A., Cramer, W., Petoukhov, V., 2000: Vegetation Continuous Description Model (VECODE). PIK Technical Report, in press.

Claussen, M., Brovkin, V., Ganopolski, A., Kubatzki, C., Petoukov, V., Rahmstorf, S., 1999a: A new model for climate system analysis. Env. Mod.Assmt., 4, 209-216.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., Pachur, H.J., 1999b: Simulation of an abrupt change in Saharan vegetation at the end of the mid-Holocene. Geophys. Res. Letters, 24 (No. 14), 2037-2040.

Dickinson R.E., Henderson-Sellers, A., Kennedy, P.J., Wilson, M.F., 1986: Biosphere-Atmosphere Trasfer Scheme BATS) for the NCAR CCM, NCAR/TN-275-STR, National Center for Atmospheric Research, Boulder, CO, 69 pp.

Ganopolski, A., Rahmstorf, S., Petoukhov, V., Claussen, M., 1998a: Simulation of modern and glacial climates with a coupled model of intermediate complexity. Nature, 391, 351-356.

Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V., Petoukhov, V., 1998b: The influence of vegetation-atmosphere-ocean interaction on climate during the mid-Holocene. Science, 280, 1916-1919.

Ganopolski, A., Petoukhov, V.K., Rahmstorf, S., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., 2000: CLIMBER- 2: A climate system model of intermediate complexity. Part II: Sensitivity experiments. Climate Dynamics, accepted.

Greve, R., 1995: Thermomechanische Verhalten polythermer Eisschilde - Theorie, Analytik, Numerik. Dissertation, Technische Hochschule Darmstadt.

Kubatzki C., Montoya M., Rahmstorf S., Ganopolski A., Claussen M., 2000: Comparison of a coupled global model of intermediate complexity and an AOGCM for the last interglacial. Climate Dyn. In press.

Petoukhov, V.K., Ganopolski, A., 1994: A set of climate models for integrated modelling of climate change impacts. Report 1-96, IIASA, Laxenburg, Austria.

Petoukhov, V.K., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., Rahmstorf, S., 2000: CLIMBER- 2: A climate system model of intermediate complexity. Part I: Model description and performance for present climate. Climate Dynamics, 16, 1-17.

Rahmstorf, S., Ganopolski, A., 1999: Long-term global warming scenarios computed with an efficient coupled climate model. Climatic Change, .

Semtner, A.J., 1976: A model for the thermodynamic growth of sea ice in numerical investigations of climate. J.Phys. Oceanogr, 6, 379-389.

Six, K. D., and Maier-Reimer, E., 1996: Effects of plankton dynamics on seasonal carbon fluxes in an ocean general circulation model, *Global Biogeochemical Cycle*s, 10, 559 - 583.

Stocker, T.F., Wright, D.G., Mysak, L.A., 1992: A zonally averaged, coupled ocean-atmosphere model for paleoclimate studies. Journal of Climate, 5, 773-797.

Yamanaka, Y., and Tajika, E., 1996: The role of the vertical fluxes of particulate organic matter and calcite in the oceanic carbon cycle: Studies using an ocean biogeochemical general circulation model. *Global Biogeochemical Cycle*s, 10, 361 - 382.

THE ECBILT CLIMATE MODEL

version June 2000

Principal Investigators

J.D. Opsteegh (opsteegh@knmi.nl)
R.J. Haarsma (haarsma@knmi.nl)
F.M. Selten (selten@knmi.nl)
S.L. Weber (weber@knmi.nl)

Royal Netherlands Meteorological Institute
P.O. ox 201
3730 AE De Bilt
The Netherlands

A Scope of the Model

ECBilt denotes the atmospheric component of a coupled atmosphere/ocean/sea-ice model of intermediate complexity, which was primarily designed to study atmosphere-ocean dynamics in the midlatitudes. A peculiarity of the atmospheric component is its use of the quasi-geostrophic approximation, with a correction for the ageostrophic terms. The inclusion of the ageostrophic terms results in an overall improvement of the model performance: the jet strength and the stormtrack are close to the observed state and the simulation of the Hadley circulation is qualitatively correct. The quasi-geostrophic approximation and the use of simplified representations of the diabatic-heating processes result in a computationally efficient climate model. Therefore, it is possible to consider climatic variability on timescales ranging from days to millennia. Focus of future work with ECBilt will be on paleo simulations as well as on ensemble scenario studies.

B Model components

- moist dynamic atmospheric model
- primitive-equation 3D ocean model
- thermodynamic sea-ice model

Atmosphere

- Spectral T21, three-level dynamic model resolving synoptic variability.
- Quasi-geostrophic approximation. The ageostrophic terms are computed diagnostically from the thermodynamic equation and included as a time- and spatially varying potential-vorticity forcing.
- Includes a prognostic equation for the total amount of precipitable water below 500 hPa. The hydrological cycle is closed by using a bucket model for soil moisture and a thermodynamic snow model.
- ECBilt1 is described in (Haarsma et al., 1997; Opsteegh et al., 1998). Recently, ECBilt2 has become available. It differs from ECBilt1 in its parameterisation package for solar and long-wave radiation. Solar radiation depends in ECBilt2 on the surface albedo of land and sea, clouds, snow and sea-ice coverage, as well as on the time-varying orbital parameters. Seasonally varying surface albedo and cloud cover are prescribed from climatology. Long-wave radiation depends on water vapor, trace gases, aerosols and clouds. The radiative terms are evaluated at two levels in the free atmosphere and at the surface.
- ECBilt2 contains a dynamically passive stratospheric layer, which is in radiative equilibrium.
- Surface air temperatures are computed diagnostically, fitting a climatological-mean temperature profile through the values at the upper two levels.
- No flux corrections are used, apart from a correction in the freshwater flux in the Arctic ocean to compensate excessive precipitation in this region.

Ocean

- The atmospheric component has been coupled to different ocean components.
- ECBilt1 was coupled to a primitive equation, flat-bottom ocean model (Haarsma et al., 1997; Opsteegh et al., 1998).
- ECBilt2 is coupled to the GFDL MOM ocean model in 5.6x5.6 degrees horizontal resolution, which is comparable to T21 used for the atmosphere.
- ECBilt2 is also coupled to the Louvain-la-Neuve CLIO ocean model (see contribution LLN to this paper).

Sea-ice

- Simplest version of the thermodynamic sea-ice model of Semtner (no advection) in the flat-bottom and GFDL MOM ocean models. In the CLIO oceanmodel a dynamic sea-ice component is used (see contribution LLN).

Miscellaneous

- The dynamic core of the atmospheric component was originally developed at the ECMWF, the parameterisation package was built in by the KNMI group located in De Bilt (the Netherlands). Hence the name ECBilt. One can pronounce this as 'easy-built' (which is not true).
- Future expansions of the model include a prognostic vegetation module and an improved land surface scheme.

C Limitations

- Variability in the tropics is substantially underestimated due to the quasi-geostrophic approximation.
- Coarse horizontal resolution (T21).

D Performance

Computational efficiency: 1000 years takes 2 weeks CPU with ECBilt2, running the atmospheric module and the ocean/sea-ice module in parallel on two processors (SG mainframe consisting of parallel Power processors).

E Applications

- The mechanism of decadal variability in the North Atlantic ocean (Selten et al., 1999) and in the Southern Ocean (Haarsma et al., 1999).
- The role of solar variability versus internally generated variability (Drijfhout et al., 1999)
- The impact of orbital forcing during the Holocene (Weber, 2000a)
- Ultra-low frequency behaviour in a 40 kyr integration (Haarsma et al., 2000)
- The study of modeled variability on multi-decadal timescales in comparison
- to proxy data (Weber, 2000b).

F References

Drijfhout, S.S., R.J. Haarsma, J.D. Opsteegh and F.M. Selten, 1999. Solar-induced varsus internal variability in a coupled climate model. Geophys.Res. Letters, 26, 205.

Haarsma, R.J., F.M. Selten, J.D. Opsteegh, G. Lenderink and Q. Liu, 1997. ECBilt, a coupled atmosphere ocean sea-ice model for climate predictability studies. KNMI Technical Report TR-195, The Netherlands.

Haarsma, R.J., F.M. Selten and J.D. Opsteegh, 2000. On the mechanism of the Antarctic cicumpolar wave. J. Climate 13, 1461-1480.

Haarsma, R.J. , J.D. Opsteegh, F.M. Selten and X. Wang, 2000. Rapid transitions and ultra-low frequency behaviour in a 40 kyr integration with a coupled AOGCM, submitted to Climate Dyn.

Opsteegh, J.D., R.J. Haarsma, F.M. Selten and A. Kattenberg, 1998. ECBILT, a dynamic alternative to mixed boundary conditions in ocean models. Tellus, 50A, 348.

Selten, F.M., R.J. Haarsma and J.D. Opsteegh, 1999. On the Mechanism of North Atlantic decadal variability. J. Climate, 12, 1956.

Weber, S.L.: 2000a, The impact of orbital forcing on the climate of an intermediate-complexity coupled model, submitted to Global and Planetary Change.

Weber, S.L.: 2000b, Holocene patterns of variability and climatic change in a coupled simulation with an intermediate-complexity model, in prep.

ECBILT-CLIO-VECODE

Principal investigators
H. Goosse (hgs@astr.ucl.ac.be)
J.-M. Campin (campin@astr.ucl.ac.be)
T. Fichefet (fichefet@astr.ucl.ac.be)
H. Renssen (renssen@astr.ucl.ac.be)

ASTR-UCL
chemin du Cyclotron, 2
B-1348 Louvain-la-Neuve
Belgium

A Scope of the model

- The objective is to analyse processes which link ocean, sea ice, atmosphere, and vegetation at mid- and high latitudes on time scales ranging from decades to thousands of years. A particular attention is paid to sea-ice processes and to the oceanic thermohaline circulation. To do so, the model has to include the more important processes at these latitudes (including synoptic atmospheric activity), while being fast enough so that long runs (> 1000 years) as well as sensitivity studies can be easily performed.
- A first group of studies consist in analysing the variability of the system using constant forcing (in the model, mainly solar constant, orbital parameters, greenhouse-gas concentrations, ice-sheet distribution). This allows to identify the feedbacks inside the system which are important to maintain this natural variability and to increase our understanding of these mechanisms.
- A second group of studies deals with the response of the system to changing conditions on varous timescales (decadal to millenium). The attention is particularly focussed on the way the feedbacks inside the system amplify or damp the initial forcing as well as on the impact of these perturbations on the natural variability.

B Model components

- Atmosphere: The atmospheric component is ECBILT (version 2) (Opsteegh et al., 1998; Selten et al., 1999), a global, spectral, quasi-geostrophic model, truncated at T21, with simple parameterizations for the diabatic heating due to radiative fluxes, the release of latent heat, and the exchange of sensible heat with the surface. The radiative flux calculations are based on a linearization of the radiation code of the ECHAM4 model (Van Dorland et al., 2000). The model contains a full hydrological cycle which is closed over land by a bucket model for soil moisture. Each bucket is connected to a nearby ocean gridpoint to define the river runoff. Accumulation of snow over land occurs in case of precipitation when the land temperature is below zero. For further details on ECBILT, see the contribution from KNMI.
- Ocean–sea ice: The CLIO model (Goosse et al., 2000a; 2000b) is made up of a primitive-equation, free-surface ocean general circulation model (Deleersnijder and Campin, 1995; Campin and Goosse, 1999) coupled to a thermodynamic–dynamic sea-ice model (Fichefet and Morales Maqueda, 1997). The ocean component includes a relatively sophisticated parameterization of vertical mixing based on Mellor and Yamada's level-2.5 model (Goosse et al., 1999), a representation of the effetcs of mesoscale eddies on the tracer distribution (isopycnal mixing and Gent-McWilliams' parameterization) as well as a parameterization of dense water flow down topographic features (Campin and Goosse, 1999). A 3-layer model, which takes into account sensible and latent heat storage in the snow–ice system, simulates the changes of snow and ice thicknesses in response to surface and bottom heat fluxes. The variation of ice compactness due to thermal processes is a function of the energy balance of the surface layer in the region occupied by leads. The impact of the subgrid-scale ice-thickness distribution on ice thermodynamics is taken into account through the use of an equivalent thermal conductivity. In the computation of ice dynamics, sea ice is considered to behave as a viscous-plastic continuum. The horizontal resolution of CLIO is 3 degrees is of $3° \times 3°$. In order to avoid the North Pole singularity, two spherical grids are patched together. The first one is a standard geographical latitude–longitude grid covering the whole World Ocean, except for the North Atlantic and the Arctic, which are represented in a spherical coordinate system having its poles on the equator. The two grids are connected to each other in the equatorial Atlantic (Deleersnijder et al., 1993). The water flow through Bering Strait is parameterized as a linear function of the cross-strait sea-level difference in accordance with the geostrophic control theory (Goosse et al., 1997). The so-called "z-coordinate" underlies the vertical discretization, with 20 levels ranging in thickness from 10 m at the surface to 750 m in the deep ocean, with 6 levels in the top 100 m.
- Vegetation: Recently, the terrestrial vegetation module developed by Brovkin et al. (1997) has been included in the coupled ECBILT–CLIO model. Based on annual mean values of several climatic variables, the VECODE model computes the evolution of the vegetation cover described as a fractional distribution of desert, tree, and grass in

each land grid cell. This vegetation cover influences the atmospheric model through the seasonally-varying surface albedo derived from the three vegetation or desert fractions. For futher details on VECODE, see the contribution from PIK.

- Coupling of the ocean and sea-ice models: ECBILT and CLIO are coupled with the OASIS software (Terray et al., 1998). The two models have different grids. Nevertheless, every atmospheric surface grid cell can contain an arbitrary fraction of open ocean (or leads), sea-ice, and land surface. It is therefore possible to achieve an exact matching of the area occupied by these three types of surface in the two models in order to conserve the heat and mass exchanged at the interface. There is no local flux correction in ECBILT–CLIO. However, the model systematically overestimates the precipitation over the Atlantic and Arctic oceans, with potential consequences for the stability of the thermohaline circulation as well as on the mass balance of the Arctic snow/sea-ice system. As a consequence, it has been necessary to artificially reduce the precipitation by 10 % over the Atlantic and by 50 % over the Arctic basins (defined here as the oceanic area north of 68°N). The corresponding water is dumped into the Pacific, a region where the model precipitation is too weak.

C Limitations

- The atmospheric model simulates the mid-latitude planetary and synoptic-scale circulations well. However, because of the quasi-geostrophic approximation, the model cannot be used to study tropical variability and tropical–extra-tropical interactions. In addition, the cloudiness is prescribed at present-day values.
- The model does not include yet an interactive representation of carbon cycle or of the ice-sheets. As a consequence, it is not possible to analyse mechanisms which include feedbacks with these two elements. In addition, it is not possible to perform simulations over time periods in which the ice sheets play a dominant role (e.g., glacial–interglacial cycles).

D Performance

- The model requires 20 min of CPU time for one year of simulation (75 years / day) on a HP N4000.
- Memory requirements: 250 Mb.

E Current applications

- Study of the decadal-to-centennial climate variability in polar regions (Goosse et al., 2000c).
- Transient runs over the Holocene.
- Analysis of the mechanisms responsible for the 8.2-yr BP cold event.

F References

Brovkin, V., A. Ganapolski, and Y. Svirezhev, 1997. A continuous climate-vegetation classification for use in climate-biosphere studies, *Ecol. Modell.*, 101, 251–261.

Campin J.-M., and H. Goosse, 1999. A parameterization of density-driven downsloping flow for a coarse-resolution ocean model in *z*-coordinate. *Tellus*, 51A, 412–430.

Deleersnijder, E., J.P. van Ypersele, and J.-M. Campin, 1993. An orthogonal curvilinear coordinate system for a World Ocean model, *Ocean Modell.*, *100*, 7–10 (+figures) (unpublished manuscript).

Deleersnijder, E., and J.-M. Campin, 1995. On the computation of the barotropic mode of a free-surface world ocean model, *Ann. Geophys.*, *13*, 675–688.

Fichefet, T., and M. A. Morales Maqueda, 1997. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, *J. Geophys. Res.*, *102*, 12609–12646.

Goosse, H., J.-M. Campin, T. Fichefet, and E. Deleersnijder, 1997. Sensitivity of a global ice–ocean model to the Bering Strait throughflow, *Clim. Dyn.*, *13*, 349–358.

Goosse, H., E. Deleersnijder, T. Fichefet and M.H. England, 1999. Sensitivity of a global coupled ocean-sea ice model to the parameterization of vertical mixing. *J. Geophys. Res.*, 104, 13,681–13,695.

Goosse, H., J.-M. Campin, E. Deleersnijder, T. Fichefet, P.-P. Mathieu, M.A. Morales Maqueda, and B. Tartinville, 2000a. Description of the CLIO model, version 3.0. *Scientific Report 2000/3*, Institut d'Astronomie et de Géophysique G. Lemaître, Louvain-la-Neuve, Belgium, 49 pp.

Goosse, H., J.-M. Campin, and B. Tartinville, 2000b. Clio 3.0: Description of some routines*.* *Scientific Report 2000/4*, Institut d'Astronomie et de Géophysique G. Lemaître, Louvain-la-Neuve, Belgium, 49 pp.

Goosse, H., F.M.Selten, R.J. Haarsma, and J.D. Opsteegh, 2000c. Decadal variability in high northern latitudes as simulated by an intermediate-complexity climate model. *Ann. of Glaciol.*, submitted.

Opsteegh, J.D., R.J. Haarsma, F.M. Selten, and A. Kattenberg, 1998. ECBILT: A dynamic alternative to mixed boundary conditions in ocean models. *Tellus*, 50A, 348–367.

Selten, F.M., R.J. Haarsma, and J.D. Opsteegh. 1999. On the mechanism of North Atlantic decadal variability. *J. Clim.*, 12, 1956–1973.

Terray, L., S. Valcke, and A. Piacentini. 1998. OASIS 2.2, Ocean–Atmosphere–Sea-Ice–Soil user's guide and reference manue*l*, *Tech. Rep. TR/CGMC/98-05*, CERFACS, Toulouse, France.

Van Dorland, R., P. Stammes, A.A.M. Holtslag, and W. Kohsiek, 2000. A longwave radiative transfer scheme for climate modelling and its evaluation with surface observations at Cabauw. *Quart. J. Roy. Met. Soc.*, in press.

The IAP RAS global climate model

version June 2000

Principal Investigators:

I.I.Mokhov (mokhov@omega.ifaran.ru)
V.K.Petoukhov (petukhov@pik-potsdam.de)
A.V.Eliseev (lesha@omega.ifaran.ru)
V.A.Semenov (vova@omega.ifaran.ru)

A.M.Obukhov Institute of Atmospheric Physics
Russian Academy of Sciences
Pyshevsky 3,
109017 Moscow
Russia

A Scope of the model

The IAP RAS global climate model is developed at the Oboukhov Institute of Atmospheric Physics of the Russian Academy of Sciences. It belongs to the class of multilayer grid-cell Earth system model of intermediate complexity. It is designed to model large scale processes (with horizontal scales of several hundreds kilometers and time scale of few days). Efficient parameterizations of smaller scale processes allow one to perform long model runs. Currently the model has the horizontal resolution of 4.5^o on latitude and 6^o on longitude and time step 5 days. Principal description of the model is given in (Petoukhov et al., 1998).

B Model components

- Statistical-dynamical atmospheric module
- Statistical dynamical oceanic module
- Energy-balance sea ice model
- Land surface / biota model

Atmosphere

- Prognostic equations for surface air temperature, lower stratospheric temperature lapse rate, lower layer specific humidity, for cross-covariations of synoptic scale fluctuations of temperature and horizontal velocity, synoptic scale eddy kinetic energy
- Large scale dynamics is treated explicitly assuming quasi-geostrophy
- Synoptic scale dynamics is parameterized in terms of large scale fields
- Linear profiles of temperature in every atmospheric layer are assumed
- Fully interactive hydrological cycle
- Radiative heating is computed using efficient algorithm
- Vertical resolution: 11 layers

Ocean

- Prognostic equation for sea surface temperature
- Ocean dynamics is treated assuming geostrophy
- Universal profiles for characteristic oceanic layers are assumed
- Vertical resolution: 3 layers

Sea ice

- Energy conserving scheme of heat storage in the sea ice
- Diagnostic equation for sea ice thickness

Land surface / biota model

- Based on BATS
- 16 vegetation and soil types
- Vertical resolution: 2 layers

Miscellaneous

- Diurnal cycle of surface air temperature is parameterized

C Limitations

- Neglection of nonlinear terms leads to the poor representation of ageostrophic atmospheric dynamics
- Coarse resolution does not allow to study processes with horizontal spatial scales less then few hundreds kilometers
- Currently only single-layer cloudiness is implemented
- Interactive carbon cycle is not implemented
- Ice sheet dynamics is not implemented
- Oceanic salinity is prescribed regarding its annual cycle
- Atmospheric ozone content is prescribed regarding its annual cycle

D Performance

Currently about 8 min per model year on the Alpha AXP 3000 / 300 MHz computer

E Applications

- Sensitivity of the diurnal cycle of surface air temperature to atmospheric CO_2 doubling (Eliseev et al., 1995)
- Intraseasonal climate variability (Mokhov et al., 1998b)
- Sensitivity of the atmospheric annual cycle of surface air temperature (Eliseev et al., 1998; Mokhov et al., 1998a)
- Quasi biennial oscillation of the atmospheric temperature (Eliseev et al., 1997)
- Quasi- and interdecadal variability of the North Atlantic Oscillation (Handorf et al., 1999a, 1999b; Mokhov et al., 2000)
- Regional climate sensitivity for Siberia under atmospheric CO_2 increase (Mokhov et al., 1997, 1998c, 1999)

F References

Eliseev, A.V., 1998: Surface air temperature annual cycle harmonics: Diagnostics from observational data and IAP RAS climate model simulations. in: Research Activities in Atmospheric and Oceanic Modelling (ed. A.Staniforth), WMO/TD no.865, CAS/JSC WGNE, World Meteorological Organization, Geneva, P.7.7-7.8.

Eliseev, A.V., K.V.Bezmenov, P.F.Demchenko, I.I.Mokhov, and V.K.Petoukhov, 1995: Modellinng of diurnal cycle under climate change. in: Proc. of The International Conference on Past, Present and Future Climate, Finland (ed.P.Heikinheimo), Publications of the Academy of Finland 6/95, Painatuskeskus, Helsinki, Finland, p.272-275.

Eliseev, A.V., I.I.Mokhov and V.K.Petukhov, 1997: Modelling the quasi-biennial oscillations of atmospheric temperature and the tendencies of its evolution under climatic changes. Izvestiya, Atmos. Ocean. Phys., v.33, p.679-687.

Handorf, D., V.K.Petoukhov, K.Dethloff, A.V.Eliseev, A.Weisheimer and I.I.Mokhov, 1999a: Decadal climate variability in a coupled atmosphere-ocean climate model of moderate complexity. J. Geophys. Res., v.104, p.27253-27275.

Handorf, D., V.K.Petoukhov, K.Dethloff, A.V.Eliseev, A.Weisheimer and I.I.Mokhov, 1999b: Climate variability at decadal and interdecadal time scales. CLIVAR Exchanges, v.4., p.21-24.

Mokhov, I.I., A.V.Eliseev and N.Yu.Vakalyuk, 1998a: Phase characteristics of SAT annual cycle: Tendencies of change from observations and model simulations. in: Research Activities in Atmospheric and Oceanic Modelling (ed. A.Staniforth), WMO/TD no.865, CAS/JSC WGNE, World Meteorological Organization, Geneva, p.7.23-7.24.

Mokhov , I.I., A.V.Eliseev, D.Handorf, V.K.Petukhov,K.Dethloff, A.Weisheimer, and D.V.Khovorostyanov, 2000: North Atlantic Oscillation: Diagnosis and modelling of interdecadal variability and its evolution. Izvestiya, Atmos. Ocean. Phys., v.36 (in press).

Mokhov, I.I., V.K.Petukhov, A.V. Eliseev and V.A.Semenov, 1997: Intra- and interannual climate variability in Asia (Siberia): Tendencies of change derived from observations and IAP RAS model simulations. in: Proc. Third Intern. Study Conf. on GEWEX in Asia and GAME, GAME International Panel Office, Research Center of Water and Biogeochemical Cycles, Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, p.347-352

Mokhov, I.I., V.K.Petukhov and V.A.Semenov, 1998b: Multiple subseasonal temperature regimes and their evolution simulated by the IAP RAS climate model. Izvestiya, Atmos. Ocean. Phys., v.34, p.163-171.

Mokhov, I.I., V.K.Petukhov, A.V.Eliseev and V.A.Semenov, 1998c: Multiscale diagnostics of water and energy cycles in Asia (Siberia) from observations and model simulations. in: Procedings of Second International Workshop on Energy and Water Cycle in GAME-Siberia, Res.Rep.IHAS. No.4, Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, p.91-98.

Mokhov, I.I., V.K.Petukhov, A.V.Eliseev and D.V.Khvorostyanov, 1999: Intra- and interdecadal quasi-cyclic climate variations an Asian regions as derived from long-term simulations of IAPRAS climate model. in: Proc. of the Third International Scientific Conference on the Global Energy and Water Cycles, Global Energy and Water Cycle Experiment, World Climate Research Program, Beijing, p.341.

Petoukhov, V.K., 1991: Dynamical-statistical modelling of large-scale climatic processes. Dr. Sci. thesis, Leningrad Hydrometorological Institute, St.Petersburg, 431 p. [in Russian].

Petoukhov, V.K., I.I.Mokhov I.I., A.V.Eliseev, and Semenov V.A., 1998. The IAP RAS global climate model. Dialogue-MSU, Moscow, 110 p.

The McGill paleoclimate model

version August 2000

Principal Investigators

L. A. Mysak (mysak@zephyr.meteo.mcgill.ca)
Z. Wang (wangz@zephyr.meteo.mcgill.ca)

Department of Atmospheric and Oceanic Sciences
and Centre for Climate and Global Change Research
805 Sherbrooke Street West
McGill University
Montreal, Quebec
Canada H3A 2K6

A Scope of the model

We have developed a new physically-based coupled atmosphere-ocean-sea ice-land surface-ice sheet model (henceforth called The McGill Paleoclimate Model (MPM)) for long-term climate change studies. The MPM incorporates the seasonal cycle. Three ocean basins, the Antarctic Circumpolar Current region and the major continents are resolved. The model variables are sectorially averaged across the different ocean basins and continents. The major reason for developing the MPM is to investigate millennial and Milankovitch timescale climate variability during the Quaternary period. In the future, the model will be applied to other geological periods.

B Model components

- Energy-moisture balance model of the atmosphere
- Zonally averaged ocean model
- Thermodynamic sea ice model
- Land surface model
- Dynamic ice sheet model

Atmosphere

- Balance for heat and moisture, no dynamics [Stocker et al., 1992; Fanning and Weaver, 1996; Wang and Mysak, 2000a].
- The meridional energy and moisture transports are parameterized by a combination of advection and diffusion processes [Wang and Mysak, 2000a].
- The zonal heat transport between land and ocean obeys a diffusion law, while the zonal moisture transport is parameterized so that the ocean always supplies moisture to the land [Wang and Mysak, 2000a].
- Resolution: 5^o in meridional direction, sectorially averaged across the different ocean basins and continents.

Ocean

- Dynamics based on vorticity conservation [Wright and Stocker, 1991; Stocker and Wright, 1991].
- The zonally averaged east-west pressure gradient is parameterized in terms of the meridional pressure gradient.
- Three zonally averaged basins, connected through the Southern Ocean south of 40°S, meridional resolution 5°, 9 vertical layers, flat bottom.

Sea ice model

- Zero-layer thermodynamic sea ice model of Semtner [1976].
- Sea ice concentration is predicted by the method of Hibler [1979].
- Advection of sea ice is prescribed [Harvey, 1988].

Land surface model

- The land surface temperature is predicted by an energy budget equation, similar to that of Ledley [1991].
- The land surface hydrological cycle is predicted by the Manabe [1969] bucket model.

Ice sheet

- The ice sheet thickness is predicted by an ice mass conservation equation [Gallee et al., 1992].
- The meridional ice flow velocity is diagnosed from the ice height.

- The bedrock depression is predicted from an isostatic adjustment model of Peltier and Marshall [1995].
- Massive iceberg calvings are prescribed to occur when the maximum ice sheet height reaches a critical value.

Time steps

- 6 hours for the atmosphere, land surface and sea ice model
- 15 days for the ocean model
- 10 years for the ice sheet model

C Limitations

- The surface wind and the meridional sea ice advection velocity are prescribed.
- A vegetation-albedo feedback, an active carbon cycle and the water vapor-temperature feedback are excluded.
- The thermodynamics of ice sheets is also not incorporated, and the net accumulation rate of ice sheets is calculated with a coarse resolution.

D Performance

- At the present time, a 30 ka integration of the MPM takes approximately 24 hours in our workstation, which is the IBM workstation RS6000/260 (PowerPC_Power3: 200 MHz; SPECfp_base_rate95: 225; RAM: 256 MB).

E Applications

- The above model (less the ice sheet component) was first used to investigate the initiation of glaciation [Wang and Mysak, 2000a]. When land ice is growing, the THC in the North Atlantic Ocean is intensified, resulting in a warm subpolar North Atlantic Ocean, which is in agreement with the observations of Ruddiman and McIntyre [1979] which describe the conditions at the beginning of the last glacial. The intensified THC maintains a large land-ocean thermal contrast at high latitudes and hence enhances land ice accumulation.
- The full five-component model (the MPM) has been then employed to study ice sheet-THC interactions [Wang and Mysak, 2000b]. After a simple iceberg calving mechanism is introduced, millennial timescale climate cycles are simulated. An iceberg calving event may also shut down the THC in the North Atlantic and hence cause large climate changes: a large equatorward advance of sea ice in North Atlantic leads to a significant cooling in northern high latitudes and a large reduction of the net accumulation rate at the grid of maximum ice sheet height. When the collapsed THC is restored, we find a large retreat of sea ice extent and hence a significant warming in northern high latitudes and an increased net accumulation rate at the grid of maximum ice sheet height.
- Lastly, the THC response to various cold climates has been investigated [Wang and Mysak, 2000c]. Generally, it is found that the response of the THC to global cooling is nonlinear: For a slightly cold climate, the North Atlantic overturning cell (NAOC) and the Pacific upwelling become intensified. For a very cold climate, the NAOC may be weakened or even collapsed. The associated Pacific upwelling for a very cold climate also becomes weak when the NAOC is weakened. When the NAOC is collapsed, intermediate water may form in the Pacific.

F References

Fanning , A. F. and A. J. Weaver, An atmospheric energy-moisture balance model: Climatology, interpentadal climate change, and coupling to an ocean general circulation model. *J. Geophys. Res.,* 101, 15111-15128, 1996.

Gallee, H, J. P. Van Ypersele, T. Fichefet, C. Tricot and A. L. Berger, Simulation of the last glacial cycle by a coupled 2-D climate-ice sheet model. Part 2: Response to insolation and CO_2. *J. Geophys. Res.,* 97, 15713-15740, 1992.

Harvey, L. D. D., Development of a sea ice model for use in zonally averaged energy balance climate model. *J. Climate*, 1, 1221-1238, 1988.

Hibler III, W. D., A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.,* 9, 815-846, 1979.

Ledley, T. S., The climatic response to meridional sea-ice transport. *J. Climate,* 4, 147-163, 1991.

Manabe, S., Climate and the ocean circulation. I: The atmospheric circulation and the hydrology of the earth surface. *Mon. Wea. Rev.,* 97, 739-774, 1969.

Peltier, W. R. and S. Marshall, Coupled energy-balance/ice-sheet model simulations of the glacial cycle: A possible connection between terminations and terrigenous dust. *J. Geophys. Res.,* 100, 14269-14289, 1995.

Ruddiman, W. F. and A. McIntyre, Warmth of the subpolar north Atlantic Ocean during northern hemisphere ice-sheet growth. *Science,* 204, 173-175, 1979.

Semtner, A. J., A model for the thermodynamic growth of sea ice in numerical investigations of the climate. *J. Phys. Oceanogr.,* 6, 379-389, 1976.

Stocker, T. F., and D. G. Wright, A zonally averaged model for the thermohaline circulation. Part II: Interocean exchanges in the Pacific-Atlantic basin system, *J. Phys. Oceanogr.*, 21, 1725-1739, 1991.

Stocker, T. F., D. G. Wright, and L. A. Mysak, A zonally averaged, coupled ocean-atmosphere model for paleoclimate studies, *J. Climate*, 5, 773-797, 1992.

Wang, Z. and L. A. Mysak, A simple coupled atmosphere-ocean-sea ice-land surface model for climate and paleoclimate studies. *J. Climate*, 13, 1150-1172, 2000a.

Wang, Z. and L. A. Mysak, Ice sheet-thermohaline circulation interactions in a climate model of intermediate complexity, *Clim. Dyn.* Submitted, 2000b.

Wang, Z. and L. A. Mysak, Response of the thermohaline circulation to cold climates, in preparation, 2000c.

Wright, D. G. and T. F. Stocker, A zonally averaged ocean model for the thermohaline circulation. I: Model development and flow dynamics. *J. Phys. Oceanogr.*, 21, 1713-1724, 1991.

The MIT Integrated Global System Model

version July 2000

Principal Investigators

Peter H. Stone (phstone@mit.edu)
Andrei Sokolov

Massachussets Institute of Technology (MIT)
Department of Earth, Atmosphere and Planetary Sciences
77 Massachusetts Avenue
Cambridge MA 02139
USA

A Scope of the Model

The MIT model is designed for simulating the global environmental changes that may arise as a result of anthropogenic causes, the uncertainties associated with the projected changes, and the effect of proposed policies on such changes. The current model includes an economic model for analysis of greenhouse and aerosol precursor gas emissions and mitigation proposals, a coupled model of atmospheric chemistry and climate, and models of natural ecosystems. All of these models are global but with appropriate levels of regional detail. In the integrated model, the combined anthropogenic and natural emissions model outputs are driving forces for the coupled atmospheric chemistry and climate model. The climate model outputs drive a terrestrial ecosystems model predicting land vegetation changes, land CO_2 fluxes, and soil composition, which feed back to the coupled chemistry/climate, and natural emissions models. A description of the integrated model, as of 1998, can be found in Prinn *et al*. (1999). The main change since then is that the two-dimensional (2D) ocean model has been replaced by a three-dimensional (3D) ocean model (see below). More details on the MIT program, the model, publications, and contact information can be found at http://web.mit.edu/globalchange/www/.

B Model components

- Model of anthropogenic emissions
- Climate model
- Atmospheric chemistry model
- Terrestrial ecosystem model
- Natural emissions model

Model of Anthropogenic Emissions

This economics model computes predictions of anthropogenic emissions of the key gases from 12 economic regions, and converts them into distributions by latitude where needed. Special provision is made for analysis of uncertainty in key influences, such as the growth of population and economic activity, and the pace and direction of technical change. Further, the model has been formulated to support analysis of a variety of emissions control policies, providing estimates of the magnitude and distribution among nations of the costs, and clarifying the ways that changes are mediated through international trade.

Climate Model

This model couples a 2D land-ocean-resolving (LO) statistical-dynamical model of the atmosphere (Sokolov and Stone, 1998) to a 3D ocean general circulation model (GCM) (Kamenkovich *et al*., 2000). The atmospheric model is a modified version of an atmospheric GCM developed at the Goddard Institute for Space Studies (GISS). Unlike energy balance models, the 2D-LO model explicitly solves the primitive equations for the zonal mean state of the atmosphere and includes parameterizations of heat, moisture, and momentum transports by large scale eddies based on baroclinic stability theory. The model's numerics and parameterizations of clouds, convection, precipitation, boundary layer processes, and surface fluxes closely parallel those of the GISS GCM (Hansen *et al*., 1983). It incorporates the radiation code of the GISS GCM which includes all significant greenhouse gases, such as H_2O, CO_2, CH_4, N_2O, CFCs, and O_3, and 11 types of aerosols. The model's horizontal and vertical resolutions are variable, but in the standard version it has 24 points in latitude and nine divisions in the vertical. The atmospheric model's climate sensitivity can be changed by varying the cloud feedback. The ocean GCM uses the MOM2 code developed at the Geophysical Fluid Dynamics Laboratory and a simplified global geometry. The resolution is coarse (about 4 degrees in the horizontal with 15 layers in the vertical) except in the boundary currents where it is increased to 1 degree. Mesoscale eddies are represented by the Gent-McWilliams parameterization. Both models are coupled to a simple thermodynamic sea-ice model. An earlier version of the climate model used a 2D mixed-layer diffusive ocean (Sokolov and Stone, 1998) in place of the ocean

GCM, and this version is still used for many studies. The 2D ocean model contains a carbon cycle (Prinn *et al*., 1999), and a carbon cycle is currently under development for the ocean GCM.

Atmospheric Chemistry Model

A 2D zonal mean model is used to calculate atmospheric composition. This is a finite difference model in latitude-pressure coordinates, and the continuity equations for trace constituents are solved in mass conservative or flux form (Wang *et al*., 1998). The local trace species tendency is thus a function of convergence due to two-dimensional advection, parameterized north-south eddy transport, and convective transports, and local true production or loss due to surface emission or deposition and atmospheric chemical reactions. The model includes 25 chemical species (among them CO_2, CH_4, N_2O, O_3, CO, H_2O, NO_x, HO_x, SO_2, sulfate aerosol, CFCs). There are 41 gas-phase and 12 heterogeneous reactions. The continuity equations for $CFCl_3$, CF_2Cl_2, N_2O, O_3, CO, CO_2, NO, NO_2, N_2O_5, HNO_3, CH_4, CH_2O, SO_2, and H_2SO_4 include convergences due to transport whereas the remaining very reactive atoms, free radicals, or molecules are assumed to be unaffected by transport because of their very short lifetimes. Water vapor and air (N_2 and O_2) mass densities are computed using full continuity equations as a part of the climate model to which the chemical model is coupled. The climate model also provides wind speeds, temperature, solar radiation flux and precipitation which are used in the chemistry formulation.

Terrestrial ecosystem model (TEM)

The TEM was developed at the Marine Biological Laboratory and is used to predict global ecosystem states (Xiao *et al*., 1997). It is a process-based ecosystem model that simulates important carbon and nitrogen fluxes and pools for 18 terrestrial ecosystems. It runs at a monthly time step. Driving variables include monthly average climate (precipitation, mean temperature and mean cloudiness), soil texture (sand, clay and silt proportion), elevation, vegetation and water availability. The model incorporates a water balance model to generate hydrological input (*e.g*., potential evapotranspiration, soil moisture). For global extrapolation, TEM uses spatially-explicit data sets at a resolution of 0.5 degrees. The global data sets include long-term average climate, potential natural vegetation, soil texture and elevation.

Natural emissions model (NEM)

The NEM simulates the emissions of N_2O and CH_4 from the terrestrial biosphere to the atmosphere (Liu, 1996). The global emission model for N_2O, which focuses on soil biogenic N_2O emissions, has a 2.5 degree spatial resolution. The model can predict daily emissions for N_2O, N_2, NH_3 and CO_2 and daily soil uptake of CH_4. It is a process-oriented biogeochemical model including soil C and N dynamic processes for decomposition, nitrification, and denitrification. The model takes into account the spatial and temporal variability of the driving variables, which include vegetation type, total soil organic carbon, soil texture, and climate parameters. Climatic influences, particularly temperature and precipitation, determine dynamic soil temperature and moisture profiles and shifts of aerobic-anaerobic conditions. The methane emission model is developed specifically for wetlands and has a spatial resolution of 1 degree. For high latitude wetlands, the emission model uses a two-layer hydrological model to predict the water table level and the bog soil temperature, which are then used in an empirical formula to predict methane emissions. For tropical wetlands, a two-factor model (temperature and water availability) is used to model the methane flux by taking into account the temperature and moisture dependence of activity of methanogens. Methane emissions from wet tundra are calculated by assuming a constant small methane flux and an emission season defined by the time period when the surface temperature is above the freezing point. The hydrological model and the two-factor model are driven by surface temperature and precipitation, which links methane.

Miscellaneous

The integrated model also includes mass-balance models of the Greenland and Antarctic ice sheets, and a mass balance model of the world's mountain glaciers is under development. These, when combined with the calculation of the thermal expansion of sea-water already included in the ocean models, will make it possible to simulate changes in sea-level.

C Limitations

- The zonal averaging of the climate and chemistry models limits the model's ability to simulate regional impacts.
- The lack of interactive ocean dynamics in the 2D ocean model limits the application of the integrated model with that version of the ocean to time scales of about 100 years.
- The lack of land-ice dynamics limits the application of the version of the integrated model with the ocean GCM to several hundreds of years.

D Performance

- Computational efficiency on a single 500 MHz CPU: A 100 year simulation with the climate model using the ocean GCM requires 10 hours; with the coupled climate-chemistry model requires 20 hours; and with the coupled climate-chemistry-TEM model requires 26 hours. The other component models have minimal computer requirements.

- Memory usage: 20 MB for coupled climate-chemistry model; 120 MB for coupled climate-chemistry-TEM model.

E Applications

- Analysis of the Kyoto Protocol: Reilly *et al*. (1999)
- Constraining uncertainties in climate model characteristics: Forest *et al*. (2000)
- Simulations of changes in the thermohaline circulation in global warming scenarios: Kamenkovich *et al*. (2000)
- Simulations of ecosystem changes in global warming scenarios: Xiao *et al*. (1997 and 1998)
- Studies of feedbacks between different components of the integrated model: Prinn *et al*. (1999)
- Studies of the impact of uncertainties on climate projections: Sokolov *et al*. (1998)

F References

Forest, C.E., M.R. Allen, P.H. Stone and A.P. Sokolov, 2000: Constraining uncertainties in climate models using climate change detection techniques. *Geophys. Res. Lett*., **27**, 569-572.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy and L. Travis, 1983: Efficient three-dimensional global models for climate studies: models I and II. *Mon. Wea. Rev*., **111**, 609-662.

Kamenkovich, I.V., A. Sokolov and P.H. Stone, 2000: A coupled atmosphere-ocean model of intermediate complexity for climate change study. *J. Climate*, submitted; (available on the Web at http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt60.pdf).

Liu, Y., 1996: Modeling the emissions of nitrous oxide (N_2O) and methane (CH_4) from the terrestrial biosphere to the atmosphere. Ph.D. thesis, Mass. Inst. of Tech., Cambridge, MA, 219pp.

Prinn, R., H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, D. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian, and Y. Liu, 1999: Integrated global system model for climate policy assessment: feedbacks and sensitivity studies. *Climatic Change*, **41**, 469-546.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Mellilo, P. Stone, A. Sokolov and C. Wang, 1999: Multi-gas assessment of the Kyoto Protocol. *Nature*, **401**, 549-555.

Sokolov, A., and P.H. Stone, 1998: A flexible climate model for use in integrated assessments. *Climate Dynamics*, **14**, 291-303.

Sokolov, A., C.Wang, G.Holian, P.Stone and R.Prinn, 1998: Uncertainty in the oceanic heat and carbon uptake and its impact on climate projections. *Geophys. Res. Lett*., **25**, 3603-3606.

Wang, C., R.G. Prinn and A. Sokolov, 1998: A global interactive chemistry and climate model: formulation and testing. *J. Geophys. Res*., **103**, 3399-3418.

Xiao, X., D.W. Kicklighter, J.M. Melillo, A.D. McGuire, P.H. Stone and A.P. Sokolov, 1997: Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: Implications for the global carbon budget. *Tellus*, **49B**, 18-37.

Xiao, X., J.M. Melillo, D.W. Kicklighter, A.D. McGuire, R.G. Prinn, C. Wang, P.H. Stone and A. Sokolov, 1998: Transient climate change and net ecosystem production of the terrestrial biosphere. *Global Biogeochemical Cycles*, 12, 345-360.

The MoBidiC Climate Model (Louvain-la-Neuve, Belgium)

version July 2000

Principal Investigators

Michel Crucifix (crucifix@astr.ucl.ac.be)
Philippe Tulkens (ptulkens@astr.ucl.ac.be)
Marie-France Loutre (loutre@astr.ucl.ac.be)
André Berger (berger@astr.ucl.ac.be)

ASTR-UCL
chemin du Cyclotron, 2
B-1348 Louvain-la-Neuve
Belgium

A Scope of the Model

The MoBidiC model is based on the LLN-2D sectorial model [Gallée et al., 1991] that has been used to study the importance of Milankovitch's astronomical theory and climate feedbacks on time scales from glacial-interglacial cycles to several millions of years. Process studies on albedo feedback linked to sea ice, boreal forest extent, water vapour content, sea level and ice sheet isostatic rebound as examples are presented in Gallée et al., 1992, Berger et al., 1993, Berger et al., 1999 and Crucifix et al., 2000a. The effect of CO_2 concentration variations on climate were also analysed [Berger et al., 1998; Loutre and Berger, 2000].

As the LLN-2D model was limited by considering the Northern Hemisphere only and by not including a representation for the ocean dynamics, a new model was designed from that basis for further studies. The MoBidiC model considers the whole Earth and includes a 3-basin, sectorially averaged dynamical ocean model [Tulkens, 1998; Crucifix et al., 2000b]. Besides, the global carbon cycle (ocean and continental biosphere) was recently embedded in. The coupling with ocean dynamics and carbon cycle allows to simulate ocean related climate events at the millennium time scale or even on shorter scales such as Heinrich events. Simulations on future climate are also performed with MoBidiC.

B Model Components

- 2-levels, zonally averaged, QG atmosphere
- multilayered radiative scheme
- continental surface with snow and dynamic vegetation
- 3 basin ocean model
- thermodynamic-dynamic sea-ice
- ocean carbon cycle

Atmosphere dynamics

- 2 vertical levels, zonally averaged quasi-geostrophic model.
- resolution : 5 deg. along the latitude.
- computes also the zonally averaged, vertically integrated WV transport.

Atmosphere radiative scheme

- up to 19 vertical layers
- sectorially averaged, each zonal band is divided in up to 13 sectors representing the continents, the oceans and the ice sheets.

Continental surface

- realistic topography
- explicit calculation of snow cover and fraction
- vertical-eddy convective flux in the atmosphere: parameterization depending on vertical stratification in the PBL.
- evaporation depending on wind, temperature and vertical stratification
- vegetation : VECODE model (2 PFT + potential desert) [Brovkin et al., 1997]

Sea ice

- 0-layer based on Semtner, 1976 and adapted by Harvey, 1988 :
- advection velocity prescribed
- leads and white ice

Ocean

- primitive equation model
- sectorially averaged over three basins (Atlantic, Pacific, Indian). All basins are interconnected in the Southern high latitudes to represent the Antarctic ocean. Atlantic and Pacific basins are interconnected in the North to represent the Arctic sea.
- "Implicit Convection"
- Parameterization of downsloping current [Campin and Goosse, 1999]
- Vertical resolution : 15 levels unequally spaced.
- Latitudinal resolution : 5 degrees.

Ocean carbon cycle

- DIC, $DI^{13}C$, DOC, $DO^{13}C$, ALK, P, O_2 using Redfield approach
- Michaelis-Menten kinetics for NPP. P is the limiting nutrient [Maier-Reimer, 1993]
- Export production partitioned between POC and DOC
- Carbonate cycling [Marchal et al., 1998] but no storage in the sediment

Time steps

- 2 day for ocean and atmosphere dynamics
- 2 days for ocean tracers, radiative scheme, land surface and hydrological cycle
- 1 year for vegetation
- seasonal cycle included

C Limitations

- the zonally averaged representation of the atmosphere prevents the study of processes linked to monsoon.
- clouds, relative surface humidity and surface drag coefficient are prescribed
- evapotranspiration is not represented.
- no ocean sediment

D Performance

- 1 cpu day for 8000 simulated years without carbon cycle.
- 1 cpu day for 7000 simulated years with carbon cycle on an ALPHA-EV6 processor.
- *memory*: 11 MB without carbon cycle 43 MB with carbon cycle

E Applications

with the LLN-2D model:

Gallée H., J.-P. van Ypersele, T. Fichefet, I. Marsiat, C. Tricot, and A. Berger, Simulation of the last glacial cycle by a coupled, sectorially averaged climate-ice sheet model. II. Response to insolation and CO_2 variation, J. Geophys. Res.,97, 15,713-15,740, 1992.

Berger A., Ch. Tricot , H.Gallée and M.F. Loutre, Water vapor, CO2 and insolation over the last glacial-interglacial cycles. Phil. Trans. R. Soc. Lond. B, 341, 253-261, 1993.

Berger A., M.F. Loutre and H. Gallée, Sensitivity of the LLN climate model to the astronomical and CO2 forcing over the last 200 kyr. Climate dynamics, 14, 615-629, 1998.

Berger A., X.S. Li and M.F. Loutre, Modelling northern hemisphere ice volume over the last 3 Ma. Quaternary Science Reviews, 18(1), 1-11, 1999.

Berger A. The role of CO_2, sea-level and vegetation during the Milankovitch-forced glacial-interglacial cycles, Workshop on "Geosphere-Biosphere Interactions and Climate", Pontifical Academy of Sciences, Vatican City, 9-13 November 1998, 1999.

Loutre M.F. and A. Berger, No glacial-interglacial cycle in the ice volume simulated under a constant astronomical forcing and a variable CO2. Geophys. Res. Lett. 27 (6), 783-786., 2000.

Crucifix M., M.F. Loutre, K. Lambeck and A. Berger, 2000a. Effect of isostatic rebound on ice volume variations during the last 200 kyr, submitted.

with MoBidiC:

Bertrand C., J.-P. van Ypersele, A. Berger, Volcanic and solar impacts on climate since 1700. Climate Dynamics, **15**, 355-367, 1999.

Crucifix, M., F. Joos, P. Tulkens and Berger A., Modelling the Physical and Biogeochemical Impacts of a Freshwater Discharge in the North Atlantic With a Model of Intermediate Complexity, submitted to proceedings of the International conference on past global changes, September 6-9, 2000.

Brovkin V., S. Levis, M.F. Loutre, M. Crucifix, A. Ganopolski, C. Kubatzki and V. Petoukhov, Stability analysis of the climate-vegetation system in the northern high latitudes, in prep.

F References on model description

Brovkin, V., A. Ganopolski and Y.Svirezhev, A continuous climate-vegetation classification for use in climate-biosphere studies, *Ecoll. Modell., 101*, 251-561, 1997.

Campin, J.M. and Goosse H., Parameterization of density-driven downsloping flow for a coarse-resolution ocean model in z-coordinate, *Tel., 51A,* 412,430, 1999.

Crucifix M., P. Tulkens, M.F. Loutre and A. Berger, a reference simulation for the present-day climate with a non-flux corrected global atmosphere-ocean-sea ice model of intermediate complexity, Progress Report 2000/1, Institut d'Astronomie et de Géophysique G. Lemaître, Université catholique de Louvain, 2000b. also available on http://www.astr.ucl.ac.be/tools/mobidic.html

Gallée G., J.-P. van Ypersele, T. Fichefet, C. Tricot and A. Berger, Simulation of the last glacial cycle by a coupled, sectorially averaged climate-ice sheet model. Part I: The climate model., J. Geophys. Res., 96 (D7), 13,139-13,161, 1991

Harvey, L.D., Development of a sea ice model for use in zonally averaged energy balance models, J. Climate*, 1, 1221-1238*, 1988

Maier-Reimer, F., Geochemical cycles in an Ocean General Circulation Model. Preindustrial Tracer Distributions, Glob. Biogeochem. Cycles, *7*, 645-677, 1993

Marchal, O., Stocker T., Joos F., A latitude-depth, circulation-biogeochemical ocean model for paleoclimate studies. Development and sensitivities, Tellus, 50B 290-316,1998

Semtner, A.J., A model for the thermodyamic growth of sea ice in numerical inverstigations of climate, J. Phys. Oceanogr., 6, 379-389, 1976.

Tulkens P., A zonally averaged model of the coupled atmosphere-ocean-sea-ice system for climate studies, PhD thesis, Institut d'Astronomie et de Géophysique G. Lemaître, 1998.

Toward a Planet Simulator: PUMA - LSG

Principal Investigators
G. Lohmann (gerrit.lohmann@dkrz.de)
E. Maier-Reimer (maier-reimer@dkrz.de)
M. Latif (latif@dkrz.de)
Max-Planck-Institute for Meteorology
Bundesstr. 55
D - 20146Hamburg
Germany

E. Kirk (kirk@dkrz.de)
K. Fraedrich (fraedrich@dkrz.de)
F. Lunkeit (lunkeit@dkrz.de)
Meteorologisches Institut, Universität Hamburg
Bundesstr. 55
D- 20146 Hamburg
Germany

A Scope of the model

An Earth system model of intermediate complexity is developed for the study of climate dynamics on decadal and millennial time-scales. The main task is to identify the driving mechanisms and potential thresholds responsible for climate transitions. Emphasis is placed on the multiple states of the system and the interaction of the dominant pattern of atmospheric variability with the ocean and land surface. In contrast to conventional time-slice experiments, the present approach is not restricted to equilibrium transitions and is capable to utilize all available data for validation. Transient simulations for the past and future climate will examine feedback mechanism in the climate system. Pathways of orbital forcing into climate response will reveal the understanding of climate records. The model explicitly resolves the three-dimensional atmospheric and oceanic dynamics and is therefore conceptually different from statistical dynamical models.
At time-scales comparable to the glacial-interglacial cycles, the importance of each Earth system component has not been estimated. At this early stage of exploration for the coupled system, it is necessary to be able to carry out a large number of sensitivity experiments. It is expected that, compared to e.g. scenario calculations for the next century, different processes will dominate Earth system interactions at such long time scales. This has to be accounted for a suitable modelling framework in order to allow cooperation between expert groups of different focus. The Earth system model shall have a modular structure with portable Fortran code. The modular structure of the model enables the user to modify model configurations according to the application. New schemes and model components can be included with a minimum of technical expense which is particularly useful for paleoclimatic applications.

B Model components

Atmosphere

The Portable University Model of the Atmosphere (PUMA) [Fraedrich et al., 1998] is based on the Reading multi-level spectral model described by Hoskins and Simmons [1975]. The model solves the primitive equations using terrain following-coordinates in the vertical. The PUMA model has been extended by relatively simple radiation and precipitation schemes. A snow model following Loth [1995] has been implemented.

Ocean

The atmospheric model has been coupled to the ocean model LSG [Maier-Reimer et al., 1993] designed especially for long-term climate studies (time step of one month). This model contains a parameterization for the bottom boundary layer [Beckmann and Döscher, 1997] which drastically improves the density-driven downslope flows [Lohmann, 1998] and is essential for the interpretation of paleoclimatic records [Lohmann and Schulz, 2000].

Sea ice model

Thermodynamic sea ice model including a simple momentum balance for advection of sea ice.

Carbon Cycle

In the LSG ocean model , the HAMOCC carbon cycle model [Maier-Reimer, 1993] is included. First experiments exist for the terrestrial biosphere model LPJ (Lund-Potsdam-Jena) [Sitch et al., 2000], which is forced with the PUMA-LSG climate. The LPJ model is a dynamic global vegetation model combining mechanistic treatments of terrestrial vegetation dynamics, carbon and water cycling.

Coupling

The present version of the model uses a T21/L5 resolution for the atmosphere and 11 vertical levels with horizontal resolution of 5 degrees for the ocean. The model contains representations of sub-grid scale fluxes over land, ice, and open sea. The coupled atmosphere-ocean-sea ice model does not require flux adjustments.

Miscellaneous

- Langrangian tracers are implemented in the atmosphere [Hardenberg, 2000; Bagliani et al., 2000].
- A sediment model is included in the marine carbon cycle [Heinze et al., 1999].

C Limitations

Limitation of the current model version is due to the missing feedbacks by cryosphere and vegetation. Further limitations are due to the simplified radiation codes used (chemistry and dust). The coarse resolution and the neglected non-linear terms in the oceanic momentum balance restrict studies to spatial scales of more than a thousand kilometers, the model underestimates interannual climate variability in the tropical Pacific.

D Performance

The required CPU time for the coupled atmosphere-ocean model is less than 8 min per year on the present Cray in Hamburg, i.e. approximate two orders of magnitude faster than complex GCMs. In the asynchronously coupled mode, where atmosphere and ocean model components take even parts in computing time, about 1000 years of model integration can be performed on one day.

Atmosphere model PUMA	7 years/1 h CPU	2 MW	Fraedrich et al., 1998
Ocean model LSG	200 years/1 h CPU	5 MW	Maier-Reimer et al., 1993
Marine carbon cycle HAMOCC3	200 years/1 h CPU	10 MW	Maier-Reimer, 1993
Planed: Terrestrial biosphere LPJ	200 years/1 h CPU	1 MW	Sitch et al., 2000

E Applications

The model components have been extensively tested in studies of paleoclimate [Winguth et al., 1999], future climate change scenarios for the next century [Lunkeit et al., 1998], and storm track variability [Frisius et al., 1998]. The model is flexible enough to turn various feedback processes off and on, to study the cause and relationships of the climate components. Simulations and sensitivity studies will focus on the following topics:

- Process of glaciation and deglaciation.
- Interaction of vegetation, atmospheric dynamics, and the oceanic circulation (e.g. vegetation-snow feedback, vegetation distribution).
- Diagnostic and prognostic calculations of atmospheric CO_2 (including carbon isotopes) on long time scales.
- Importance of northern versus southern hemispheric forcing and Atlantic-Pacific teleconnections.
- Dependence of climate variability on the background state.
- Simulation of the last glacial cycle.

F References

Bagliani, F. Fraedrich, J. Hardenberg, F. Lunkeit, 2000: Lagrangian tracer homogenization and dispersion in a simplified atmospheric GCM. Il Nuovo Cimento (in press).

Beckmann, A., and R. Döscher, 1997: A method for improved representation of dense water spreading over topography in geopotential-coordinate models. J. Phys. Oceanogr., 27, 581-591.

Fraedrich, K., E. Kirk, and F. Lunkeit, 1998: Portable University Model of the Atmosphere, DKRZ Report 16. (http://dome.dkrz.de/kirk/puma/puma.html)

Frisius, T, Lunkeit, F., Fraedrich, K., and James, I. N., 1998: Storm-track organization and variability in a simplified atmospheric global circulation model. Q. J. R. Meteorol. Soc., 124, 1019-143.

Hardenberg, J., K. Fraedrich, F. Lunkeit, A. Provenzale, 2000: Transient chaotic mixing during a baroclinic life cycle. CHAOS, 10, 122-134.

Heinze, C., E. Maier-Reimer, A. M. E. Winguth, and D. Archer, 1999: A global oceanic sediment model for long-term climate studies. Global Biogeochemical Cycles, 13, 221-250.

Hoskins, B. J., and A. J. Simmons, 1975: A multi-layer spectral model and the semi-implicit method. Q. J. R. Meteorol. Soc., 101, 1231-1250.

Lohmann, G., 1998: The Influence of a near-bottom Transport Parameterization on the Sensitivity of the Thermohaline Circulation. J. Phys. Oceanogr., 28, 2095-2103.

Lohmann, G., and Schulz, M., 2000: Reconciling Bølling warmth with peak deglacial meltwater discharge. Paleoceanography, (in press).

Loth, B., 1995: Die Schneedecke als Komponente des Klimasystems und ihre Modellierung. Max-Planck-Institut für Meteorologie. Examensarbeit Nr. 32.

Lunkeit, F., S. E. Bauer, and K. Fraedrich, 1998: Storm tracks in a warmer climate: Sensitivity studies with a simplified global circulation model. Clim. Dyn., 14, 813-826.

Maier-Reimer, E., 1993: Geochemical cycles in an ocean general circulation model. Preindustrial Tracer Distributions. Global Biogeochemical Cycles, 7, 645-677.

Maier-Reimer, E., U. Mikolajewicz, and K. Hasselmann, 1993: Mean circulation of the Hamburg LSG OGCM and its sensitivity to the thermohaline surface forcing. J. Phys. Oceanogr., 23, 731-757.

Sitch, S., Prentice, I. C., Smith, B., and LPJ consortium members, 2000: A coupled model of vegetation dynamics and the terrestrial carbon cycle. in: S. Sitch, The role of vegetation dynamics in the control of atmospheric CO_2 content. Lund, Sweden.

Winguth, A., D. Archer, E. Maier-Reimer, U. Mikolajewicz, and J.-C. Dupplessy,1999: Sensitivity of the paleonutrient tracer distribution and deep-sea circulation to glacial boundary conditions. Paleoceanogr., 14, 304-323.

The UVic Earth System Climate Model

Principal Investigator

Andrew Weaver (weaver@uvic.ca)
Michael Eby (eby@uvic.ca)

University of Victoria
PO Box 3055
Victoria, BC, V8W3P6
Canada

A Scope of the model

The UVic Earth System Climate Model consists of a three dimensional ocean general circulation model coupled to a thermodynamic/dynamic sea ice model, an energy-moisture balance atmospheric model with dynamical feedbacks, and a thermomechanical land ice model. We include a full three-dimensional OGCM as we believe horizontal ocean gyre transports are fundamental to the stability and variability of the thermohaline circulation, and as we believe the latter is important for climate/paleoclimate change/variability on decadal and longer timescales. In order to keep our model computationally efficient we use a reduced complexity atmosphere model.
Our model is publicly available (upon request) from http://climate.uvic.ca/climate-lab/model.html.

B Model components

Atmospheric Model

The atmospheric model is loosely based on the energy-moisture balance model of Fanning and Weaver (1996). Atmospheric heat and freshwater transports are parameterised through Fickian diffusion and precipitation is assumed to occur when the relative humidity reaches greater than 85%. Moisture transport can also be accomplished through advection if this option is chosen. Precipitation over land is assumed to instantaneously return to the ocean via one of 33 observed river drainage basins. Ice and snow albedo feedbacks are included in the coupled model by locally reducing the latitudinal profile of the coalbedo. The EMBM includes a parameterisation of the water vapour/planetary longwave feedback (Thompson and Warren 1982), although the radiative forcing associated with changes in atmospheric CO_2 is externally imposed as a reduction of the planetary long wave radiative flux. A specified lapse rate is used to reduce the surface temperature over land where there is topography. The model uses prescribed present day winds in its climatology. A dynamical wind feedback is included which exploits a latitudinally-varying empirical relationship between atmospheric surface temperature and density.

Ocean Model

The ocean component of the coupled model is a fully nonlinear three-dimensional ocean general circulation model based on the GFDL Modular Ocean Model 2.2 (Pacanowski, 1996) with a global resolution of a 3.6° (zonal) by 1.8° (meridional) and 19 vertical levels. We also have options for the inclusion of a brine-rejection parameterisation (Duffy et al. 1999, 2000).

Sea Ice Model

The coupled model incorporates various options for the representation of sea ice thermodynamics and thickness distribution. The elastic-viscous-plastic reheology of Hunke and Dukowicz (1997) is used to represent dynamics. The standard version of the model uses Hibler (1979) thermodynamics although options for multi-category and multi-level thermodynamics exist (Bitz et al. 2000; Holland et al 2000 a,b).

Ice Sheet Model

The UBC thermomechanical ice sheet model of Marshall and Clarke (1997) is included in the model.

Ocean Chemistry

An abiotic ocean carbon cycle model is currently included. A full ocean carbon cycle model (including ocean biota) will be added shortly in collaboration with K. Caldeira at Lawrence Livermore National Laboratories.

Vegetation/Land Surface Components

We are currently exploring options for the inclusion of land surface processes, dynamic vegetation, and a terrestrial carbon cycle component.

Other Developments

Our code is currently being parallelized for use on MPP type machines. We are also developing parameterizations of cloud feedbacks.

C Limitations

- The UVic ESCM model presently does not have sophisticated treatment of land surface processes, although as noted above, we are moving towards the inclusion of dynamic vegetation and land surface schemes.
- Cloud feedbacks are not currently incorporated directly, although simple parametrisations for these are being developed.
- Only atmospheric surface dynamics are included
- Internal tropical variability is not captured

References cited above:

Hibler III WD (1979) A dynamic thermodynamic sea ice model. J Phys Oceanogr 9(4): 815-846}

Hunke EC, Dukowicz JK (1997) An elastic-viscous-plastic model for sea ice dynamics. J Phys Oceanogr 27(9): 1849-1867}

Marshall SJ, Clarke GKC (1997a) A continuum mixture model of ice stream thermomechanics in the Laurentide Ice Sheet, 1. Theory. J Geophys Res 102(B9): 20599-20613

Pacanowski, R.C., 1995. GFDL Ocean Group Tech. Rep. No. 3, GFDL/NOAA, Princeton, NJ.

Thompson, S.J. and S.G. Warren, 1982. Parameterization of outgoing infrared radiation derived from detailed radiative calculations. *J. Atmos. Sci.* **39**: 2667-2680.

D Performance

Current Speed of Model:

From 50-150 years per CPU day on our IBM SP2 nodes.

E Applications

References for papers in which various versions of the model has been used:

Fanning, A.F. and A.J. Weaver, 1996: An atmospheric energy moisture-balance model: climatology, interpentadal climate change and coupling to an OGCM. *Journal of Geophysical Research*, 101, 15111–15128.

Murdock, T.Q., A.J. Weaver and A.F. Fanning, 1997: Paleoclimatic response of the closing of the Isthmus of Panama in a coupled ocean-atmosphere model. *Geophysical Research Letters*, 24, 253–256.

Fanning, A.F. and A.J. Weaver, 1997: Temporal-geographical meltwater influences on the North Atlantic conveyor: Implications for the Younger Dryas, *Paleoceanography*, 12, 307–320.

Fanning, A.F. and A.J. Weaver, 1997: A horizontal resolution and parameter sensitivity study of heat transport in an idealized coupled climate model, *Journal of Climate*, 10, 2469–2478.

Fanning, A.F. and A.J. Weaver, 1997: On the role of flux adjustments in an idealized coupled model. *Climate Dynamics*, 13, 691–701.

Fanning, A.F. and A.J. Weaver, 1998: Thermohaline variability: The effects of horizontal resolution and diffusion. *Journal of Climate*, 11, 709–715.

Weaver, A.J., M. Eby, A.F. Fanning and E.C. Wiebe, 1998: Simulated influence of carbon dioxide, orbital forcing and ice sheets on the climate of the last glacial maximum. *Nature*, 394, 847–853.

Weaver, A.J., 1999: Extratropical subduction and decadal modulation of El Niño. *Geophysical Research Letters*, 26, 743–746.

Duffy, P.B., M. Eby and A.J. Weaver, 1999: Effects of sinking of salt rejected during formation of sea ice on results of a global ocean-atmosphere-sea ice climate model. *Geophysical Research Letters*, 26, 1739-1742.

Poussart, P.F., A.J. Weaver and C.R. Barnes, 1999: Late Ordovician glaciation under high atmospheric CO_2: A coupled model analysis. *Paleoceanography*, 14, 542–558.

Wiebe, E.C. and A.J. Weaver, 1999: On the sensitivity of global warming experiments to the parametrisation of sub-grid scale ocean mixing. *Climate Dynamics*, 15, 875–893.

Weaver, A.J. and E.C. Wiebe, 1999: On the sensitivity of projected oceanic thermal expansion to the parameterisation of sub-grid scale ocean mixing. *Geophysical Research Letters*, 26, 3461–3464.

Holland, M.M., A.J. Brasket and A.J. Weaver, 2000: The impact of rising atmospheric CO_2 on low frequency North Atlantic climate variability. *Geophysical Research Letters*, 27, 1519–1522.

Weaver, A.J., P.B. Duffy, M. Eby and E.C. Wiebe, 2000: Evaluation of ocean and climate models using present-day observations and forcing. *Atmosphere-Ocean*, 38, 271–301.

Duffy, P.B., M. Eby and A.J. Weaver, 2000: Climate model simulations of effects of increased atmospheric CO_2 and loss of sea ice on ocean salinity and tracer uptake. *Journal of Climate*, in press.

Holland, M.M., C.M. Bitz, M. Eby and A.J. Weaver, 2000: The role of ice ocean interactions in the variability of the North Atlantic thermohaline circulation. *Journal of Climate*, in press.

Bitz, C.M., M.M. Holland, A.J. Weaver and M. Eby, 2000: Simulating the ice-thickness distribution in a coupled climate model. *Journal of Geophysical Research*, submitted.

Yoshimori, M., A.J. Weaver, S.J. Marshall and G.K.C. Clarke, 2000: Glacial termination: Sensitivity to orbital and CO_2 forcing in a coupled climate system model. *Climate Dynamics*, submitted.

Weaver, A.J., M. Eby, C.M. Bitz, P. B. Duffy, T. L. Ewen, A. F. Fanning, M.M. Holland, A. MacFadyen, A. Schmittner, H. Wang, E.C. Wiebe, M. Yoshimori: The UVic Earth System Climate Model: Model description, climatology and applications to past, present and future climates. In preparation.