Table of EMICs
(Earth System Models of Intermediate Complexity)

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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. Moreover, 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 capacity. 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. The first Table of EMICs was discussed in a multi-authored paper by [Claussen et al., 2002, Climate Dynamics, 18]. Several EMIC intercomparison workshops followed which include studies of sensitivity to changes in atmospheric CO_2 concentrations [Petoukhov et al., 2005, Climate Dynamics, in press], to historical land cover change [Brovkin et al., 2005, Climate Dynamics, submitted), and an assessment of the stability of the Atlantic meridional overturning circulation [Rahmstorf et al., 2005, submitted].

The Table of EMICs is produced by the principal investigators, and the principal investigators are responsible for the description of their models. The Table is updated every two years, and new EMICs are included. Thanks are due to Johann Grüneweg, PIK, for editorial assistance.

Content

The Bern 2.5D climate model

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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, 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, Stocker, 1991, Stocker, 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, 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, Stocker, 2000].

Additional tracers: Chlorofluorocarbons CFC11 and CFC12, and radionuclides ^{231}Pa and ^{230}Th [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, Stocker, 1991, Stocker, Wright, 1991b, Stocker et al., 1992a, Wright, Stocker, 1992, Wright et al., 1995, Wright et al., 1998, Schmittner et al., 2000a, Schmittner, Stocker, 2000].

Dynamics of the thermohaline circulation [Stocker, Wright, 1991a, Stocker et al., 1992b, Lehman et al., 1993, Wright, 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, Schmittner, 1997, Schmittner, Stocker, 1999, Schmittner et al., 2000b].

Effects of ocean circulation changes on atmospheric radiocarbon [Stocker, Wright, 1996, Stocker, Wright, 1998, Marchal et al., 2001].

Influence of the thermohaline circulation on sea level projections [Knutti, Stocker, 2000].

F References

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

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

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

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

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

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

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

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

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

Marchal, O., Stocker, T.F., Joos, F., 1999a: 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. Clark, P.U., Webb, R.S., Keigwin, L.D. (eds.). Am. Geophys. Union, Washington, D.C.. Geophysical Monograph, 112, 263-284.

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

Marchal, O., François, R., Stocker, T.F., Joos, F., 2000: Ocean thermohaline circulation and sedimentary ^{231}Pa/^{230}Th ratio. Paleoceanogr., 15, 625-641.

Marchal, O., Stocker, T.F., Muscheler, R., 2001: Atmospheric radiocarbon during the Younger Dryas: Production, ventilation, or both? Earth and Planetary Science Letters, 185, 383-395.

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

Schmittner, A., Stocker, T.F., 2000: A seasonally forced ocean-atmosphere model for paleoclimate studies. J. Clim.. Submitted.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Wright, D.G., Stocker, T.F., 1993: Younger Dryas experiments. In: Ice in the Climate System. Peltier, W.R. (ed.). NATO ASI Ser., I, 12, Springer Verlag, 395-416.

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

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

CLIM*BER*-2

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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.
Individual components of CLIMBER and coupling between them are described in detail in [Petoukhov et al., 2000, Claussen et al., 1999, Brovkin et al., 2003, Calov et al, 2005a].

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, Petoukhov et al., 2003]. 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, Mysak, 1992]. **MUZON** is a multibasin (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, 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, 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 [Calov et al., 2005a].

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., 2001].

The role of the ocean during the Last Glacial Maximum [Ganopolski et al., 1998a].

Dansgaard-Oeschger and Heinrich events [Ganopolski, Rahmstorf, 2001ab, 2002, Calov et al., 2002, Mogensen et al., 2002, Ganopolski, 2003, Claussen et al., 2003, Roche et al., 2004].

The last glacial inception [Khodri et al., 2003, Calov et al., 2005ab].

Pliocene-Pleistocene transition [Haug et al, 2005].

Snow-ball Earth hypothesis [Donnadieu et al., 2004].

8.2 Ky BP event [Bauer et al, 2004].

Oceanic oxygen-18 at the present day and LGM [Roche et al, 2004].

Atmosphere-ocean-vegetation interaction during the Holocene, Eemian [Ganopolski et al., 1998b, Claussen et al., 1999b, Kubatzki et al., 2000, Wasson, Claussen, 2002].

Holocene carbon cycle [Brovkin et al., 2002].

Historical deforestation [Brovkin et al., 1999].

Boreal and tropical deforestation [(Ganopolski et al., 2001].

Climate variability during last millennium [Bauer et al., 2003].

Deforestation / Afforestation and carbon cycle [Claussen et al., 2001].

Stability of atmosphere-biosphere interaction [Brovkin et al., 2002].

Dynamics of the thermohaline circulation in a global warming context [Rahmstorf, Ganopolski, 1999, Ganopolski, Rahmstorf, 2002].

F References

Bauer, E., Claussen, M., Brovkin, V., Huenerbein, A., 2003: Assessing climate forcings of the Earth system for the past millennium. Geophys. Res. Lett., 30, 6, 1276, doi:10.1029/2002GL016639.

Bauer, E., Ganopolski, A., Montoya, M., 2004: Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. Paleoceanography, 19, 3, Art. No. PA3014.

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., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., Andreev, A., 2002: Carbon cycle, Vegetation and Climate Dynamics in the Holocene: Experiments with the CLIMBER-2 Model. Global Biogeochemical Cycle, 16, 4, 1139, doi. 10.1029/2001GB001662.

Brovkin, V., Levis, S., Loutre, M.F., Crucifix, M., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., 2002: Stability analysis of the climate-vegetation system in northern high latitudes. Climatic Change, 57, 119-138.

Brovkin, V., Claussen, M., Driesschaert, E., Fichefet, T., Kicklighter, D., Loutre, M.-F., Matthews, D., Ramankutty, N., Schaeffer, M., Sokolov, A., 2005: Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. Climate Dyn. Submitted.

Calov, R., Ganopolski, A., Petoukhov, V., Claussen, M., Greve, R., 2002: Large-scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model. Geophys. Rev. Lett., 29, 24, 2216, doi:10.1029/2002GL016078.

Calov, R., Ganopolski, A., Claussen, M., Petoukhov, V., Greve, R., 2005: Transient simulation of the last glacial inception. Part I: Glacial inception as a bifurcation of the climate system. Clim Dyn. In press.

Calov, R., Ganopolski, A., Petoukhov, V., Claussen, M., Brovkin, V., Kubatzki, C., 2005: Transient simulation of the last glacial inception with an atmosphere-ocean-vegetation-ice sheet model: Part II: Sensitivity and feedback analysis. Clim Dyn. 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, 14, 2037-2040.

Claussen, M., Brovkin, V., Petoukhov, V., Ganopolski, A., 2001: Biogeophysical versus biogeochemical feedbacks of large-scale land-cover change. Geophys. Rev. Letters, 26, 6, 1011-1014.

Claussen, M., Brovkin, V., Ganopolski, A., Kubatzki, C., Petoukhov, V., 2002: Climate Change in Northern Africa: The past is not the future. Climatic Change, 57, 99-118.

Claussen, M., Ganopolski, A., Brovkin, V., Gerstengarbe, F.-W., Werner, P., 2003: Simulated Global-Scale Response of the Climate System to Dansgaard-Oeschger and Heinrich events. Clim Dynam., 21, 361-370.

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

Donnadieu, Y., Ramstein, G., Fluteau, F., Roche, D., Ganopolski, A., 2004: The impact of atmospheric and oceanic heat transports on the sea-ice-albedo instability during the Neoproterozoic. Clim Dynam,. 22, 293-306.

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., Rahmstorf, S., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., 2001: CLIMBER- 2: A climate system model of intermediate complexity. Part II: Sensitivity experiments. Climate Dynamics, 17, 735-751.

Ganopolski, A., Rahmstorf, S., 2001a: Rapid changes of glacial climate simulated in a coupled climate model. Nature, 409, 153-158.

Ganopolski, A., Rahmstorf, S., 2001b: Stability and variability of the thermohaline circulation in the past and future: a study with a coupled model of intermediate complexity, in The ocean and rapid climate change: Past, Present, and Future. American Geophysical Union, Washington, D.C., 261-275.

Ganopolski, A., Rahmstorf, S. 2002: Abrupt glacial climate changes due to stochastic resonance. Phys Rev Lett, 88, 3, 038501.

Ganopolski, A,2003: Glacial Integrative modelling. Philos T Roy Soc A, 361,1871-1884.

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

Haug, G.H., Ganopolski, A., Sigman, D.M., Rosell-Mele, A., Swann, G.E.A., Tiedemann, R., Jaccard, S.L., Bollmann, J., Maslin, M.A., Leng, M.J., Eglinton, G., 2005: North Pacific seasonality and the glaciation of North America 2.7 million years ago. Nature, 433, 821-825.

Khodri, M., Ramstein, G., Paillard, D., Duplessy, J.C., Kageyama, M, Ganopolski, A., 2003: Modelling the climate evolution from the last interglacial to the start of the last glaciation: the role of Arctic Ocean freshwater budget. Geophys. Rev. Lett., 30, doi: 10.1029/2003GL017108.

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., 16, 799-814.

Mogensen, I.A., Johnsen, S.J., Ganopolski, A., Rahmstorf, S., 2002: An investigation of rapid warm transitions during MIS2 and MIS3 using Greenland ice-core data and the CLIMBER-2 model. Annals of Glaciology, 35, 398-402.

Petoukhov, V., 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.

Petoukhov, V., Ganopolski, A., Claussen, M., 2003: POTSDAM-a set of atmosphere statistical-dynamical models: theoretical background. PIK Report, 81, 136 p.

Petoukhov, V., Claussen, M., Berger, A., Crucifix, M., Eby, M., Eliseev, A.V., Fichefet, T., Ganopolski, A., Goosse, H., Kamenkovich, I., Mokhov, I.I., Montoya, M., Mysak, L.A., Sokolov, A., Stone, P., Wang, Z., Weaver, A.J., 2005: EMIC Intercomparison Project (EMIP--CO_2): Comparative analysis of EMIC simulations of climate, and of equilibrium and transient responses to atmospheric CO2 doubling. Climate Dynamics. In press.

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

Roche, D., Paillard, D., Cortijo, E., 2004: Constraints on the duration and freshwater release of Heinrich event 4 through isotope modelling. Nature, 432, 379-382.

Roche, D., Paillard, D., Ganopolski, A., Hoffmann, G., 2004: Oceanic oxygen-18 at the present day and LGM: equilibrium simulations with a coupled climate model of intermediate complexity. EPSL, 218, 317-330.

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., Maier-Reimer, E., 1996: Effects of plankton dynamics on seasonal carbon fluxes in an ocean general circulation model. Global Biogeochemical Cycles, 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.

Wasson, R.J., Claussen, M., 2002: Earth system models: a test using the mid-Holocene in the southern hemisphere. Quat. Sci. Rev., 21, 819-824.

Yamanaka, Y., 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 Cycles, 10, 361 - 382.

CLIMBER-3α

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A Scope of the model

As its predecessor, CLIM*BER* -2, CLIM*BER*-3α is designed to explore the dynamic behaviour of the natural Earth system. Compared to fully coupled atmosphere-ocean general circulation models (AOGCMs), it has a computationally faster atmospheric component and thus allows a large number of long-term simulations. Thanks to the included ocean general circulation model (OGCM), CLIM*BER*-3α is especially suitable to investigate the role of the ocean in climate dynamics. CLIMBER-3α is described in [Montoya et al, 2005a].

B Model components

POTSDAM-2, statistical dynamical model of the atmosphere.
MOM-3, oceanic general circulation model.
ISIS, thermodynamic-dynamic sea ice model.
ASI, atmosphere-surface (land/ocean) interface.
VECODE, dynamic global vegetation model.

Ocean

The oceanic component is based on a modified version of the **GFDL OGCM, MOM-3** [Pacanowski, Griffies, 1999] with a horizontal resolution of 3.75° x 3.75° and 24 variably spaced vertical levels. The low-diffusive tracer advection scheme by [Prather, 1986] allows simulations with very low isopycnal and vertical diffusion [Hofmann, Maqueda, 2005]. The model has a nonlinear explicit free surface and incorporates several mixing parameterisations, such as eddy-induced advection of tracers following [Gent, McWilliams, 1990], enhanced mixing over rough topography [Hasumi, Suginohara, 1999] and the K-profile parameterisation [Large et al., 1994].

Atmosphere

POTSDAM-2 is a 2.5-dimensional statistical dynamical model taken from CLIM*BER*-2 [Petoukhov, Ganopolski, 1994, Claussen et al., 1999, Petoukhov et al, 2000]. The horizontal resolution was increased to 7.5° in longitude and 22.5° in latitude. Thus an atmospheric grid box covers 2 longitudinal and 6 latitudinal ocean grid boxes.

Atmosphere-surface interface

CLIM*BER* -2's **ASI**, based on the Biosphere-Atmosphere Transfer Scheme (BATS) [Dickinson et al., 1986] is included. CLIM*BER*-2's simplified landmask was replaced by interpolation of ETOPO5 on the ocean's 3.75° horizontal resolution. ASI includes an atmosphere-ocean coupler which has been extensively modified for coupling to MOM-3. Due to the ocean's nonlinear explicit free surface, the coupling of the atmosphere and ocean is done directly via freshwater fluxes; a salt flux is restricted to brine rejection due to sea-ice formation or melting. The penetration of shortwave radiation into the water column as well as into sea-ice is taken into account. The only flux correction applied is a wind anomaly model based on the NCEP-NCAR reanalysis.

Sea ice

The thermodynamic-dynamic snow and sea ice model with elasto-viscous-plastic rheology is described in [Fichefet, Maqueda, 1997]. It implements one layer of ice and one layer of snow on a 3.75° x 3.75° horizontal grid.**ISIS**, thermodynamic-dynamic sea ice model.

Terrestrial biosphere

The terrestrial vegetation module VECODE is a reduced-form dynamic global vegetation model taken from CLIM*BER*-2]Brovkin et al., 2002]. The horizontal resolution was increased to that of the atmosphere (7.5° x 22.5°).

Marine biosphere and oceanic carbon cycle

CLIMBER-3α is coupled to the marine ecosystem model by [Six, Maier, Reimer, 1996]. The model allows to simulate the dynamics of phytoplankton, zooplankton, $CaCO_3$, detritus, phosphate, silicate, oxygen, dissolved inorganic carbon (DIC) and alkalinity, prognostically [Hofmann and colleagues, 2005].

C Limitations

Coarse resolution in the atmosphere, also compared to the ocean. A wind-anomaly model is used as boundary conditions for the momentum equation of the ocean. No interannual variability.

D Performance

Computational efficiency: ca. 100 years per CPU day (IBM p655) without carbon cycle, Memory usage: ca. 250 MB.

E Applications

Sensitivity of ocean circulation to vertical diffusivity [Mignot et al., 2005].
Dynamic sea level changes following a weakening of the thermohaline circulation [Levermann et al., 2005].
Doubling of CO_2-scenario [Petoukhov et al., 2005a, Petoukhov et al., 2005b].
Validation of conceptual models [Levermann, Griesel, 2004].
Coupling of Bottom Water and Deep Water in the Atlantic [Levermann, Mignot, 2005].
Sea level rise and global temperature under different CO_2-scenarios [Nawrath et al., 2005].
Paleoclimate time-slice and transient studies [Montoya and colleagues, 2005].
Sensitivity to model parameters (resolution, oceanic viscosity) [Montoya et al, 2005b].
Multistability of the thermohaline circulation [Mignot and colleagues, 2005].
Role of energy and location of mixing for the thermohaline circulation [Griesel, Montoya, 2005].

F References

Brovkin, V., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., Andreev, A., 2002: Carbon cycle, vegetation and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. Global Biogeochem. Cycles, 16, 4, 1139.

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

Dickinson, R.E., Henderson-Sellers, A., Kennedy, P.J., Wilson, M., 1986 Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR CCM NCAR/TN-275-STR.

Fichefet, T. Maqueda, M.A.M., 1997: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. Journal of Geophysical Research, 102, 12609.

Gent, P.R., McWilliams, J.C., 1990: Isopycnal Mixing in Ocean Circulation Models. Journal of Physical Oceanography, 20, 150.

Griesel, A., Montoya, M., 2005: Parameterizing vertical mixing based on fixed available energy: the role of mixing location and numerical diffusion for Atlantic overturning dynamics. In preparation.

Hasumi, H., Suginohara, N., 1999: Effects of locally enhanced vertical diffusivity over rough bathymetry on the world ocean circulation. Journal of Geophysical Research, 104**,** 12646.

Hofmann, M. and colleagues, 2005: Sensitivity of marine ecosystems towards THC variations, in preparation.

Hofmann, M., Maqueda, M.A.M., 2005: A more accurate scheme for tracer advection in ocean models. Monthly Weather Review, in preparation.

Large, W.G., McWilliams, J.C., Doney, S.C., 1994: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. ROG, 32**,** 363.

Levermann, A., Griesel, A., 2004: Solution of a Model for the Oceanic Pycnocline Depth: Scaling of Overturning Strength and Meridional Pressure Difference. Geophysical Research Letters, 31**,** L17302.

Levermann, A., Griesel, A., Hofmann, M., Montoya, M., Rahmstorf, S., 2005: Dynamic sea level changes following changes in the thermohaline circulation. Climate Dynamics. In press.

Levermann, A., Mignot, J., 2005: Diffusive coupling of Bottom Water to Deep Water in the Atlantic. Geophysical Research Letters, in preparation.

Mignot, J. and colleagues, 2005: In preparation.

Mignot, J., Levermann, A., Griesel, A., 2005: A decomposition of the Atlantic Meridional Overturning Circulation into physical components using its sensitivity to vertical diffusivity. Journal of Physical Oceanography. Submitted.

Montoya, M., Griesel, A., Levermann, A., Mignot, J., Hofmann, M., Ganopolski, A., Rahmstorf, S., 2005a: The Earth System Model of Intermediate Complexity CLIMBER-3α. Part I: description and performance for present day conditions. Climate Dynamics, under revision.

Montoya, M., Griesel, A., Levermann, A., Mignot, J., Hofmann, M., Ganopolski, A., Rahmstorf, S., 2005b: The Earth System Model of Intermediate Complexity CLIMBER-3α. Part II: model sensitivity. Climate Dynamics, in preparation.

Montoya, M. and colleagues, (2005: In preparation.

Nawrath, S., Levermann, A., Rahmstorf, S., 2005: Ensemble of long-term CO_2 scenarios with a coupled climate model: Temperature and sea level rise. Climate Dynamics, in preparation.

Pacanowski, R.C., Griffies, S.M., 1999: The MOM-3 manual. Tech. Rep., 4.

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

Petoukhov, V., 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.

Petoukhov, V., Claussen, M., Berger, A., Crucifix, M., Eby, M., Eliseev, A., Fichefet, T., Ganopolski, A., Goosse, H., Kamenkovich, I., Mokhov, I., Montoya, M., Mysak, L., Sokolov, A., Stone, P., Wang, Z., Weaver, A., 2005a: EMIC Intercomparison Project (EMIP-CO_2): Comparative analisis of EMIC simulations of current climate and equilibrium and transient responses to atmospheric CO_2 doubling. Part I: pre-industrial climate simulation. Climate Dynamics. Accepted.

Petoukhov, V., Claussen, M., Berger, A., Crucifix, M., Eby, M., Eliseev, A., Fichefet, T., Ganopolski, A., Goosse, H., Kamenkovich, I., Mokhov, I., Montoya, M., Mysak, L., Sokolov, A., Stone, P., Wang, Z., Weaver, A., 2005b: EMIC Intercomparison Project (EMIP-CO_2): Comparative analisis of EMIC simulations of current climate and equilibrium and transient responses to atmospheric CO_2 doubling. Part II: equilibrium and transient responses to CO_2 doubling. Climate Dynamics. Accepted.

Prather, M.J., 1986: Numerical advection by conservation of second-order moments. Journal of Geophysical Research, 91, 6671.

Six, K.D., Maier-Reimer, E. 1996: Effects of phytoplankton on seasonal carbon fluxes in an ocean general circulation model. Global Biogeochem. Cycles, 10, 4, 559.

GENIE

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A Scope of the model

GENIE (Grid ENabled Integrated Earth system model) is a framework being used to produce a range of Earth system models covering several orders of magnitude in integration speed. The emphasis is on computationally efficient models and the use of Grid computing technology to enable long integrations and large ensemble experiments, for both paleo, and future, Earth system studies. The framework is designed to promote modularity (i.e. interchangeable components), scalability (i.e. variable resolution) and traceability (across our model spectrum and to more highly resolved models). The ocean-atmosphere-sea ice model C-GOLDSTEIN (Edwards and Marsh, 2005) was modularized as a starting point, and several components have been, or are being, added to the framework.

B Model components

IGCM, a 3D spectral general circulation model of the atmosphere.
EMBM, a 2D Energy-Moisture Balance Model of the atmosphere.
GOLDSTEIN, a 3D frictional geostrophic model of the ocean with linear drag.
BIOGEM, an ocean biogeochemistry model.
SEDGEM, an ocean sediment model.
Thermodynamic sea ice model.
Advection-diffusion and thermodynamic sea ice model.
Elastic-Viscous-Plastic (EVP) sea ice rheology.
GLIMMER, a 3D ice sheet model.
ENTS, a minimal land surface physics and carbon cycle model.
GENIE-land, a more complex land surface physics model based on MOSES.
TRIFFID, a dynamic global vegetation model.

Atmosphere

IGCM is a modified version of the 3-D spectral Reading Intermediate General Circulation Model IGCM3.1 [de Forster et al., 2000], based on [Hoskins, Simmons, 1975]. The convection scheme has been replaced with that of [Tiedke, 1993]. The baseline resolution is T21 with 7 levels, but this can be readily altered. We are exploring T11 and T42 horizontal resolutions. Well-mixed atmospheric gases are represented by individual reservoirs. There will be an additional module for transporting dust.

EMBM is a modified version of the 2-D Energy-Moisture Balance Model of [Weaver et al., 2001]. It includes a diffusive-advective model of atmospheric heat and moisture transport, using imposed annual or seasonal mean wind fields. Atmospheric carbon dioxide (CO_2) can be prescribed as an input parameter or treated as a variable (single reservoir) when coupled to ocean and land biogeochemistry.

Ocean

GOLDSTEIN (Global Ocean Linear Drag Salt & Temperature Equation Integrator) is a fast, intermediate complexity, 3-D frictional geostrophic model with linear drag [Edwards, 1996, Edwards, Marsh, 2005]. Momentum is strongly damped in this system, but tracer dynamics are equivalent to primitive equation GCMs. Three versions are in use with different resolution: “lego box” 18×18×8 equal horizontal area cells [Edwards, Shepherd, 2002]; “baseline” 36×36×8, equal horizontal area, realistic geometry [Edwards, Marsh, 2005]; 36×60×8 longitude-latitude with higher resolution toward the poles. Bottom topography can be included in all versions and it is easy to vary the number and spacing of depth intervals.

Sea ice

The sea-ice model from C-GOLDSTEIN is a standard Semtner-Hibler, zero-thickness, thermodynamic model with advection by surface currents and a diffusive term applied to thickness and areal fraction.

The thermodynamics-only sea-ice scheme from the IGCM is an alternative in the framework.

The EVP rheology is based on [Hunke, Dukowicz, 1997] and will soon be added to the framework.

Ocean biogeochemistry

BIOGEM is an ocean BIOGEochemistry Model derived from an existing 2.5D model (SUE) [Ridgwell, 2001]. It handles the biological and chemical transformation (and in some cases sinking) of a variable number of chemical species (tracers): DIC (dissolved inorganic carbon), DIC ^{13}C, DIC ^{14}C, PO_4, Alk, O_2, NO_3 (not yet as a nutrient), DOM C (carbon in dissolved organic matter), DOM ^{13}C, DOM ^{14}C, DOM N, DOM P, DOM O_2, Ca, B. Also air-sea exchange of: N_2, N_2O, CH_4, SF_6, CFC11, CFC12. BioGeM is being expanded to include the cycling of nitrogen, silicic acid and iron. Each additional tracer introduces a modest additional computational burden and thus they are treated as options at composition time.

Ocean sediments

SEDGEM is a marine SEDiment bioGEochemistry Model [Ridgwell, 2001]. It includes a representation of opal diagenesis [Ridgwell, 2001] and fairly standard schemes for the dissolution of calcium carbonate and the in situ re-mineralisation of organic matter. It also allows for a (small) sub-grid-scale ensemble of sedimentary columns within each grid cell, which permits realistic results even for rather coarse spatial resolution. Asynchronous coupling to the ocean circulation and biogeochemistry.

Terrestrial biosphere

ENTS is an Efficient Numerical Terrestrial Scheme capturing land surface physics (overflowing bucket) and vegetation and soil carbon reservoirs in each land grid cell.

GENIE-land is a simplified version of the full MOSES Hadley Centre land-surface scheme [Cox et al., 1999] developed by Peter Cox and also being used by the UVic group. It allows a longer time step than full MOSES (~6 hours rather than 30 minutes) by excluding fast processes (e.g. canopy interception). A land surface source of dust to the atmosphere will be added.

TRIFFID is the full Hadley Centre model capturing vegetation dynamics and carbon storage in vegetation and soil. The model will be extended to provide sources of alkalinity, dissolved inorganic carbon, phosphate, nitrate, silicic acid, iron and any other trace metals required, to the ocean.

Ice sheets

GLIMMER is based on an existing ice sheet model [Payne, 1999]. It uses a projected grid scaleable over 20-100+ km grid cells. Physics available include; mass balance calculations using energy balanc and day-degree calculations; coupled ice flow, thermodynamics and ice-thickness evolution; and isostasy. A more advanced model of fast-flow regimes will also be incorporated. The code is written in such a way that it can run as multiple instances. Thus the individual ice sheets of the world (Greenland, Antarctica, Laurentide, Scandinavian etc) can be modeled on separate, local grids and the need for high-resolution global coverage is avoided.

Miscellaneous

Coupling of model components occurs through a master ‘genie.f’ routine that passes arguments.

C Limitations

Limitations are specific to the chosen modules: The EMBM is a 1-layer representation of the atmosphere with no active dynamics and trivial radiative calculation. The IGCM is limited in computational efficiency. In GOLDSTEIN momentum is strongly damped and eddies cannot be represented. BIOGEM does not model ecosystem dynamics. ENTS has no distinction of vegetation types. The framework lacks an atmospheric chemistry module. Impact assessment and economic modules have been coupled to C-GOLDSTEIN, but are not yet within the GENIE framework.

D Performance

Computational efficiency: for C-GOLDSTEIN 4000 years per cpu hour (1.8 GHz AMD 64), approximately 100 times slower with IGCM. Memory usage: for C-GOLDSTEIN 10 MB.

E Applications

Bi-stability of the ocean thermohaline circulation [Marsh et al., 2004].

Tracing the ^{18}O signals associated with glacial meltwater pulses [Rohling et al., 2004].

Uncertainties due to transport parameter sensitivity [Edwards, Marsh, 2005].

Factorial analysis of marine carbon cycle controls on atmospheric CO_2 [Cameron et al., submitted].

Parameter estimation using an ensemble Kalman filter [Annan et al., 2005, Annan et al., 2005].

Climate forecasting using ensemble methods [Hargreaves et al., 2004, Hargreaves, Annan, 2005].

Optimization of components [Price et al., 2004, Beltran et al., submitted, Price et al., submitted].
Grid-enabled simulations [Gulamali et al., 2003, Gulamali et al., 2004].
Integrated assessment modelling [Drouet et al., 2005].

F References

Annan, J.D., Hargreaves, J.C., Edwards, N.R., Marsh, R.: 2005: Parameter estimation in an intermediate complexity earth system model using an ensemble Kalman filter. Ocean Modelling, 8, 135-154.

Annan, J.D., Lunt, D.J., Hargreaves, J.C., Valdes, P.J., 2005: Parameter estimation in an atmospheric GCM using the Ensemble Kalman Filter. Nonlinear Processes in Geophysics, 12, 363-371.

Beltran, C., Edwards, N.R., Haurie, A., Vial, J.-P., Zachary, D.S.: Oracle-based optimization applied to climate model calibration. Environmental Modelling and Assessment. Submitted.

Cameron, D.R., Lenton, T.M., Ridgwell, A.J., Shepherd, J.G., Marsh, R.J., Yool, A.: A factorial analysis of the marine carbon cycle controls on atmospheric CO_2. Glob. Biogeochem. Cycl.. Accepted.

Cox, P.M., Betts, R.A., Bunton, C.B., Essery, R.L.H., Rowntree, P.R., Smith, J., 1999: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. Climate Dynamics, 15, 183-203.

de Forster, P.M., Blackburn, M., Glover, R., Shine, K.P., 2000: An examinatation of climate sensitivity for idealised climate change experiments in an intermediate general circulation model. Climate Dynamics. 16, 833-849.

Drouet, L., Edwards, N.R.. Haurie, A..2005: Coupling Climate and Economic Models in a Cost-Benefit Framework: A Convex Optimization Approach. Environmental Modelling and Assessment. In press.

Edwards, N.R., 1996: Unsteady similarity solutions and oscillating ocean gyres. J. mar. Res., 54, 793-826.

Edwards, N.R., Shepherd, J.G., 2002: Bifurcations of the thermohaline circulation in a simplified three-dimensional model of the world ocean and the effects of inter-basin connectivity. Climate Dynamics, 19, 31-42.

Edwards, N.R., Marsh, R.J., 2005: Uncertainties due to transport-parameter sensitivity in an efficient 3-D ocean-climate model. Climate Dynamics, doi 10.1007/s00382-004-0508-8.

Gulamali, M.Y., Lenton, T.M., Yool, A., Price, A.R., Marsh, R.J., Edwards, N.R., Valdes, P.J., Wason, J.L., Cox, S.J., Krznaric, M., Newhouse, S., Darlington, J., 2003: GENIE: Delivering e-Science to the environmental scientist. In: e-Science All Hands Meeting 2003, EPSRC, Nottingham, 145-152.

Gulamali, M.Y., McGough, A.S., Marsh, R.J., Edwards, N.R., Lenton, T.M., Valdes, P.J., Cox, S.J., Newhouse, S.J., Darlington, J., GENIE, 2004: Performance guided scheduling in GENIE through ICENI. In: UK e-Science All Hands Meeting 2004, Nottingham.

Hargreaves, J.C., Annan, J.D., Edwards, N.R., Marsh, R., 2004: An efficient climate forecasting method using an intermediate complexity Earth system model and the ensemble Kalman Filter. Climate Dynamics, 745-760.

Hargreaves, J.C., Annan, J.D., 2005: Using ensemble prediction methods to examine regional climate variations under global warming scenarios. Ocean Modelling, doi 10.1016/j.ocemod.2004.12.004.

Hoskins, B.J., Simmons, A.J., 1975: A multi-layer spectral model and the semi-implicit method. Q. J. R. met. Soc., 101, 637-655.

Hunke, E.C., Dukowicz, J.K., 1997: An elastic-viscous-plastic model for sea-ice dynamics. Journal of Physical Oceanography, 27, 1849-1867.

Marsh, R.J., Yool, A., Lenton, T.M., Gulamali, M.Y., Edwards, N.R., Shepherd, J.G., Krznaric, M., Newhouse, S., Cox, S.J., 2004: Bistability of the thermohaline circulation identified through comprehensive 2-parameter sweeps of an efficient climate model. Climate Dynamics, 23, 761-777.

Payne, A.J., 1999: A thermomechanical model of ice flow in West Antarctica. Climate Dynamics, 15, 115-125.

Price, A.R., Xue, G., Yool, A., Lunt, D.J., Lenton, T.M., Wason, J.L., Pound, G.E., J., C.S., 2004: Tuning GENIE Earth System Model Components using a Grid Enabled Data Management System. In: UK e-Science All Hands Meeting 2004, Nottingham.

Price, A.R., Xue, G., Yool, A., Lunt, D.J., Valdes, P.J., Lenton, T.M., Wason, J.L., Pound, G.E., J., C.S.: Optimisation of GENIE Earth system model components using a Grid-enabled data management system. In: Concurrency and Computation: Practice and Experience. Accepted.

Ridgwell, A.J., 2001: Glacial-interglacial perturbations in the global carbon cycle. University of East Anglia, Norwich, 134.

Rohling, E.J., Marsh, R., Wells, N.C., Siddall, M., Edwards, N.R., 2004: Similar meltwater contributions to glacial sea level changes from Antarctic and northern ice sheets. Nature, 430, 1016-1021.

Tiedke, M., 1993: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Monthly Weather Review, 117, 1779-1800.

Weaver, A.J., Eby, M., Wiebe, E.C., Bitz, C.M., Duffy, P.B., Ewen, T.L., Fanning, A.F., Holland, M.M., McFadyen, A., Matthews, H.D., Meissner, K.J., Saenko, O.A., Schmittner, A., Wang, H., Yoshimori, M., 2001: The UVic Earth System Climate Model: Model Description, Climatology, and Applications to Past, Present and Future Climates. Atmosphere-Ocean, 39.

Williamson, M.S., Lenton, T.M., Shepherd, J.G., Edwards, N.R.: An Efficient Numerical Terrestrial Scheme (ENTS) for Fast Earth System Modelling. Ecol. Model. Submitted.

The IAP RAS global climate model

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A Scope of the model

The IAP RAS global climate model is developed at the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences. It belongs to the class of the multilayer grid-cell Earth system models of intermediate complexity. It is designed to simulate the large scale processes. Efficient parameterizations of the smaller scale processes allow one to perform long model runs. Currently the model has the horizontal resolution of 4.5o on latitude and 6o on longitude and time step 5 days. The basic description of the model is given in [Petoukhov et al., 1998].

B Model components

Atmosphere

Horizontal resolution 4.5*6 deg lat*lon, vertical resolution 11 layers (up to 80 km).
3-D QG large-scale dynamics.
synoptic-scale dynamics is parameterised in terms of the Gaussian ensemble statistics.
linear profiles of temperature in every atmospheric layer are assumed.
interactive hydrological cycle.

Ocean

Horizontal resolution 4.5*6 deg lat*lon, , vertical resolution 3 layers.
prognostic equation for sea surface temperature.
ocean dynamics is treated assuming geostrophy.
universal profiles for characteristic oceanic layers are assumed.
salinity is prescribed.

Sea ice

Energy conserving scheme of heat storage in the sea ice.
diagnostic equation for sea ice thickness (based on the values of SAT and SST),

Land surface

2-layer, 16 vegetation and soil types, based on BATS,

Terrestrial biosphere

Vegetation annual cycle is based on BATS,
vegetation succession is neglected.

Oceanic biosphere

neglected.

Inland ice

Prescribed according to the present-day distribution.

C Limitations

Atmospheric water vapor content is parameterized via temperature (atmospheric relative humidity is fixed).
Annual cycles of oceanic salinity, ozone content and vegetation are prescribed.
Interactive carbon cycle is not implemented.
Ice sheet dynamics is not implemented.

D Performance

About 5000 model years per astronomic day at the Intel Xeon Dual Server. Memory requirement ~1.5GB.

E Applications

Future projections of the climate change under anthropogenic forcing [Mokhov et al., 2002, Mokhov et al., 2005].

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 of the surface air temperature annual cycle to climate change [Eliseev, Mokhov, 2003, Eliseev et al., 1998, 2004a, b, 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 in the Northern Hemisphere under atmospheric CO_2 change [Demchenko et al., 2002, Mokhov et al., 1997, 1998c, 1999, 2002, 2005].

F References

Anisimov, O.A., Demchenko, P.F., Eliseev, A.V., Mokhov, I.I., Nechaev, V.P., Velichko, A.A., 2002: Effect of climate change on permafrost in the past, present and future. Izvestiya, Atmos. Oceanic Phys., 38 ,suppl.1, 25-39.

Demchenko, P.F., Eliseev, A.V., Mokhov, I.I., Nechaev, V.P., Velichko, A.A., 2001: Sensitivity of permafrost cover in the Northern Hemisphere to climate change. CLIVAR Exchanges, 6, 9-11.

Demchenko, P.F., Velichko, A.A., Eliseev, A.V., Mokhov, I.I., Nechaev, V.P., 2002: Dependence of permafrost conditions on global warming: Comparison of models, scenarios, and paleoclimatic reconstructions. Izvestiya, Atmos. Oceanic Phys., 38, 143-151.

Demchenko, P.F., Eliseev, A.V., Arzhanov, M.M., Mokhov, I.I., 2005: Sensitivity of the thermal conditions, favorable for the permafrost formation, to the time rate of the global warming. Izvestiya, Atmos Oceanic Phys.. In press.

Eliseev, A.V., Bezmenov, K.V., Demchenko, P.F., Mokhov, I.I., Petoukhov, V.K., 1995: Modelling of diurnal cycle under climate change. Publ. Acad. Finland, 6/95, 272-275.

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

Eliseev, A.V., Mokhov, I.I., 2003: Amplitude-phase characteristics of the annual cycle of surface air temperature in the Northern Hemisphere. Adv. Atmos. Sci., 20, 1-16.

Eliseev, A.V., Guseva, M.S., Mokhov, I.I., Rubinshtein, K.G., 2004: Amplitude-phase characteristics of the annual cycle of surface temperature: Comparison of AGCM output and reanalysis data. Izvestiya. Atmos. Oceanic Phys., 40, 381-393.

Eliseev, A.V., Mokhov, I.I., Rubinstein, K.G., Guseva, M.S., 2004: Atmospheric and coupled model intercomparison in terms of amplitude-phase characteristics of surface air temperature annual cycle. Adv. Atmos. Sci., 21, 837-847.

Golitsyn, G.S., Mokhov, I.I., Khon, V.C., 2000: Diagnostics and modelling of hydrologic regime changes in Caspian Sea basin in XX and XXI centuries. In: Ecological Problems of Caspy, RAS / NAS USA, Moscow, Kirov, 2000, 28-37.

Golubyatnikov, L.L., Mokhov, I.I., Denisenko, E.A., Tikhonov, V.A., 2005: Model estimates of climate change impact on the vegetation cover and carbon sink from the atmosphere. Izvestiya, Atmos. Oceanic Phys., 41, 19-28.

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

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

Meleshko, V.P., Golitsyn, G.S., Govorkova, V.A., Demchenko, P.F., Eliseev, A.V., Kattsov, V.M., Malevsky-Malevich, S.P., Mokhov, I.I., Nadezhina, E.D., Semenov, V.A., Sporyshev, P.V., Khon, V.C., 2004: Possible anthropogenic climate changes in Russia in the 21st century: Estimates with ensemble of climate models. Rus. Meteorol. Hydrol., 4, 38-49.

Mokhov, I.I., Petoukhov, V.K., Eliseev, A.V., Semenov, A.V., 1997: Intra- and interannual climate variability in Asia (Siberia): Tendencies of change derived from observations and IAP RAS model simulations. Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, 347-352.

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

Mokhov, I.I., Petoukhov, V.K., Eliseev, A.V., Semenov, V.A., 1998c: Multiscale diagnostics of water and energy cycles in Asia (Siberia) from observations and model simulations. Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, Res. Rep. IHAS, 4, 91-98.

Mokhov, I.I., Eliseev, A.V., Handorf, D., Petoukhov, V.K., Dethloff, K., Weisheimer, A., Khovorostyanov, D.V., 2000: North Atlantic Oscillation: Diagnosis and modelling of interdecadal variability and its evolution. Izvestiya, Atmos. Ocean. Phys., 36, 605-616.

Mokhov, I.I., Khon, V.C., 2000: Diagnostics and modelling of hydrologic regime changes in Siberian rivers basins in XX and XXI centuries. In: Ecology of flood-lands of Siberian Rivers and Arctic рек. Томск. SST, 2000, C.8-16 (in Russian).

Mokhov, I.I., 2002: Siberian rivers runoff in the 21st century. Zemlya i Vselennaya (Earth and Univerce), 6, 3-10 (in Russian).

Mokhov, I.I., Demchenko, P.F., Eliseev, A.V., Khon, V.C., Khvorostyanov, D.V., 2002: Estimation of global and regional climate changes during the 19th-21$_{st}$ centuries on the basis of the IAP RAS model with consideration for anthropogenic forcing. Izvestiya, Atmos Oceanic Phys., 38, 555-568.

Mokhov, I.I., Khon, V.C., 2002: Model scenarios of changes in the runoff of Siberian rivers in the 21st century. Dokl. Earth Sci., 383A, 329-332.

Mokhov, I.I., Khon, V.C., 2002: Hydrological regime in Siberian rivers basins: Model scenarios of changes in the 21st century. Rus. Meteorol. Hydrol., 8, 77-93.

Mokhov, I.I., Semenov, V.A., Khon, V.C., 2003: Estimates of possible regional hydrologic regime changes in the 21st century based on global climate models. Izvestiya, Atmos. Ocean. Phys., 39, 130-144.

Mokhov, I.I., 2004: Climate studies in Russia in 1999-2002. Izvestiya, Atmos. Oceanic Phys., 40, 127-133.

Mokhov, I.I., Eliseev, A.V., Demchenko, P.F., Khon, V.C., Akperov, M.G., Arzhanov, M.M., Karpenko, A.A., Tikhonov ,V.A., Chernokulsky, A.V., Sigaeva, E.V., 2005: Climate changes and their assessment based on the IAP RAS global model. Dokl. Earth Sci., 402, 2.

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

ISAM-2

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A Scope of the model

Integrated Science Assessment Model (ISAM) Framework of the Earth System utilizes an intermediate approach by retaining fairly sophisticated climate, chemistry, carbon and methane cycles, but simplifying the advanced ocean dynamics. Therefore, ISAM modeling framework provides far greater computational efficiency and allows extensive explorations of key physical, chemical, and biological interactions among individual components of the earth system (atmosphere, ocean, cryosphere, land, and biosphere). The Integrated Science Assessment Model (ISAM) currently consists of a number of coupled modules. These coupled modules include regional representations of: the carbon cycle through modeling oceanic and biospheric processes; the global natural emissions model through modeling biomass and biogenic emissions and atmospheric chemistry; and global climate, through an energy balance climate model that relates radiative forcing changes to the impact on global temperature and hydrological cycle. Below is a brief description of individual components of the latest version of ISAM.

B Model components

Atmosphere

Atmosphere component consists of vertically integrated energy-moisture balance equations. All variables are calculated over land and ocean surfaces separately. The surface air temperature is calculated based on the thermodynamic energy flux balance equation, which includes solar radiation, upward and downward long wave radiation, sensible and latent heat flux. Specific humidity is determined by the vertically integrated moisture balance equation. Evaporation is calculated using a bulk formula, and precipitation is assumed to occur either in the form of rainfall or snowfall whenever the relative humidity exceeds a critical value. The meridional resolution of the module is consistent with the ocean module. The solar and the long-wave radiation absorbed by the atmosphere are calculated based on the radiative transfer model of [Jain et al., 2000]. The module is described in more detail in [Cao, Jain, 2005a].

Ocean

The geographical configuration of the model has a latitudinal resolution of 10° with each latitude band divided into one or more ocean and/or land bands in order to resolve major ocean basins and continents. The ocean module resolves major ocean basins: the Atlantic, Pacific, and Indian Ocean, which are connected through the zonally well-mixed Southern Ocean at about 40°S. The processes of advection, diffusion, and convection determine changes of temperature and salinity. The ocean module is largely based on the zonally averaged 2-D ocean model developed by [Wright, Stocker, 1992], [Harvey, 1992], and [Hovine, Fichefet, 1994], but with some important extensions. First, in contrast to the horizontal/vertical mixing scheme used in these models, we adopt three different mixing schemes: horizontal/vertical mixing, isopycnal mixing, and Gent-McWilliams mixing. Second, in each mixing scheme the vertical/diapycnal diffusivity is calculated in terms of static stability. Third, full seasonal cycles and zonally averaged ocean bottom topography are both resolved in the model. The ocean component is driven directly by the heat and freshwater fluxes calculated from atmosphere component without the use of the ‘flux adjustment’.

Sea ice

A thermodynamic/dynamic sea ice component is included in the ISAM based on the one-layer thermodynamics model of [Semtner, 1976]. Ice surface temperature is calculated based on the energy balance at ice surface. The energy balance at both ice surface and ice bottom determines the zonal mean ice fraction and thickness. The model accounts for changes in ice fraction and thickness due to sea ice diffusion and advection.

Ocean carbon cycle

ISAM model currently includes an inorganic ocean carbon cycle component based primarily on the protocols of Ocean Carbon Cycle Model Intercomparison Project (OCMIP) [Orr et al., 1999]. The model simulates two carbon-related passive tracers: dissolved inorganic carbon (DIC) and radiocarbon (^{14}C).

Terrestrial ecosystem

The module simulates the carbon fluxes to and from different compartments of the terrestrial biosphere with 0.5^o x 0.5^o spatial resolution. Each grid cell is completely occupied by at least one of the twelve natural land coverage classifications and/or croplands; and by at least one of the 105 soil types. Within each grid cell, the carbon dynamics of each land-coverage classification are described by an ecosystem model consisting of ground vegetation (GV) representing herbaceous carbon reservoirs; non-woody tree part (NWT) represent-ing foliage, flowers and roots in transition; and woody tree parts (WT) representing branches, boles, and most root material of trees; two litter reservoirs (DPM and RPM), represent litter input from above and below ground litter biomass plant parts; and three soil reservoirs (microbial biomass (BIO), humified organic matter (HUM), and inert organic matter (IOM)). Within each grid cell, the model simulates the processes of evapotranspiration, plant photosynthesis and respiration, carbon allocation among plant organs, litter production, and soil organic carbon decomposition. The model also includes effects of biomass re-growth in response to feedback processes such as CO_2 fertilization and temperature effects on photosynthesis and respiration. Plant and soil carbon stocks for land-coverage classifications are also influenced by agriculture, forest, and non-forest change cover activities [Jain, Yang, 2004].

Biomass burning

Biomass burning emissions for key reactive greenhouse gases (CO, NMHCs, and NOx) and CO_2 are calculated at 0.5^o x 0.5^o spatial resolution by multiplying total burnt area within each grid cell with available fuel load (AFL) or burnable plant material, combustion completeness or efficiency for vegetation, emission factor of a gas using the standard method for estimating emissions from biomass burning. The AFL for each grid cell is calculated using the terrestrial component of the ISAM.

Biogenic emissions

Biogenic emissions for key indirect GHGs (e.g., isoprene, monoterpene, other reactive volatile organic compounds (ORVOC), CO, and NO) are calculated at 0.5^o x 0.5^o spatial resolution by multiplying a prescribed emission factor by foliar density, environmental adjustment factor, and escape efficiency. The terrestrial model is used to calculate net primary productivity (NPP) that drives the estimate of foliar density.

C Limitations

The climate ocean carbon cycle components of the ISAM do not account yet the following: longitudinal resolution, atmospheric dynamics processes, marine biota, and ice-sheet.

D Performance

The ISAM coupled climate-ocean-terrestrial biosphere model takes about 12,000 yrs per CPU day on 1.6 GHz Opteron Workstation.

E Applications

An ECMIC, ISAM-2.5D, Part 1: Description of climate component and the role of ocean mixing parameterizations in simulated climate [Cao, Jain, 2005a].

An ECMIC, ISAM-2.5D, Part 2: Description of carbon cycle component and the role of ocean mixing parameterizations in simulated uptake for natural and bomb radiocarbon and anthropogenic CO_2 [Cao, Jain, 2005b].

Modeling the effects of two different land lover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change [Jain, Yang, 2005].

Assessing the effectiveness of direct injection for ocean carbon sequestration under the influence of climate change [Jain, Cao, 2005].

ISAM Model estimates of global biomass burning emissions for reactive greenhouse gases (CO, NMHCs, and NOx) and CO_2 from two satellite burned area data sets [Jain et al., 2005].

ISAM Model Estimates of Global Biogenic Emissions for Key Indirect Greenhouse Gases [Tao, Jain, 2005].

Spatial and temporal radiative forcing and global warming potentials of about 40 greenhouse gases [Jain et al., 2000a, Jain et al., 2000b].

F References

Cao, L., Jain, A.K., 2005a: An Earth System Model of Intermediate Complexity: ISAM-2.5D: part 1: description of climate component and the role of ocean mixing parameterizations in simulated climate. J.Geophys. Res.- Ocean. Submitted.

Cao, L., Jain, A.K., 2005b: An Earth System Model of Intermediate Complexity: ISAM-2.5D: part 2: description of carbon cycle component and the role of ocean mixing parameterizations in simulated uptake for natural and bomb radiocarbon and anthropogenic CO_2. J.Geophys. Res.- Ocean. Submitted.

Jain, A.K., Tao, Z., Gillespie, C., 2004: ISAM Model Estimates of Global Biomass Burning Emissions for Reactive Greenhouse Gases (CO, NMHCs, and NOx) and CO_2 from Two Satellite Burned Area Data Sets. Global Biogeochemical Cycles, revised.

Jain, A.K., Cao, L., 2005: Assessing the effectiveness of direct injection for ocean carbon sequestration under the influence of climate change. Geophy. Res. Lett. Submitted.

Jain, A.K., Yang, X., 2005: Modeling the effects of two different land lover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change. Global Biogeochemical Cycles. In press.

Tao, Z., Jain, A.K., 2005: ISAM Modeling of Global Biogenic Emissions for Key Indirect Greenhouse Gases and Their Response to Atmospheric CO_2 increases and Changes in Land Cover and Climate. J.Geophys. Res.- Atmosphere. Submitted.

LOVECLIM

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A Scope of the model

The objective is to analyse processes which link ocean, sea ice, atmosphere, ice sheets and vegetation on timescales ranging from decades to thousands of years as well as the interactions between climate change and the global carbon cycle. A particular attention is paid to the high latitudes and to the role of sea-ice processes and 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 consists in analysing the behaviour and the variability of the system using constant forcing. This allows to identify the feedbacks inside the system and to increase our understanding of some important mechanisms.

A second group of studies deals with the response of the system to changing conditions on various timescales (decadal to millennial). The attention is particularly focused 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

LOVECLIM is an acronym made from the names of the five different models that have been coupled to built the Earth system model: LOch–Vecode-Ecbilt-CLio-agIs Model (LOVECLIM).

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 parameterisations 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 grid point 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, Campin, 1995, Campin, Goosse, 1999] coupled to a thermodynamic–dynamic sea-ice model [Fichefet, Morales Maqueda, 1997]. The ocean component includes a relatively sophisticated parameterisation 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 parameterisation of dense water flow down topographic features [Campin, 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 of 3 degrees by 3 degrees. 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 parameterised 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

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 further details on VECODE, see the contribution from PIK.

Ice sheets

ECBILT-CLIO-VECODE has been coupled to Huybrecht's model [Huybrecht, 2002], named AGISM (Antarctica and Greenland Ice-Sheet Model). It is a three dimensional thermomechanical model which simulates the ice flow, the bedrock evolution and the mass balance at the ice-sheet surface. The AGISM is based on the positive degree-day method. The model is forced by the atmosphere through the surface temperature and precipitation over the ice sheets. The model of the Antarctic ice sheet is also forced by the ocean through the heat flux at the ocean–ice-shelf interface [Beckman, Goosse, 2003]. The horizontal resolution is 10 km in latitude and longitude, and there are 31 layers in the ice along the vertical. The AGISM having a high resolution regarding the other components, the forcing from the atmosphere and the ocean is computed in perturbation mode.

Carbon cycle

The terrestrial carbon cycle is simulated by VECODE. LOCH is a three-dimensional model of the oceanic carbon cycle developed by [Mouchet et al., 1997]. It simulates the evolution of the dissolved inorganic carbon, alkalinity, phosphates, organic products, silica, oxygen as well as organic and inorganic ^{13}C and ^{14}C on the same grid as CLIO. The model includes a representation of the meridional diffusion in the atmosphere enabling it to compile the carbon fluxes from the biomass and from the ocean to produce a global carbon-dioxide concentration in the atmosphere. The time step is one day, i.e. the same as the physics of the ocean model.

Coupling of the atmosphere and ocean–sea-ice models

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 ocean 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 over the Atlantic and 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 reasonably well. However, because of the quasi-geostrophic approximation, using the model to study tropical variability and tropical–extra-tropical interactions must be considered with great caution. In addition, the cloudiness is prescribed at present-day values.

D Performance

The model requires 15min of CPU time for one year of simulation (100 years / day) on a Compaq ES45, Alpha ev68/1250MHz.

Memory requirements: 1800 MB.

E Current applications

Climate changes during the last 2000 years [Goosse et al., 2004a, Goosse, Renssen, 2005, Goosse et al., 2005a, b].

Future climate change [Goosse, Renssen, 2001, Schaeffer et al., 2002, 2004].

Climate of the Holocene and previous interglacials [Renssen et al., 2003, 2005a, b].

Climate of the LGM [Timmermann et al., 2005].

Study of the decadal-to-centennial climate variability in polar regions [Goosse et al., 2001, 2002, 2003].

Analysis of the mechanisms responsible for the 8.2-yr BP cold event [Renssen et al., 2001, 2002].

Effect of vegetation change on climate [(Renssen et al., 2002].

Influence of solar and volcanic forcing on climate [Goosse et al., 2004b].

F References

Beckmann, A., Goosse, H., 2003: A parameterization of ice shelf-ocean interactions for climate models. Ocean Modelling, 5, 2, 157-170.

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

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

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

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

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

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

Goosse, H., Deleersnijder, E., Fichefet, T., England, M.H., 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., Campin, J.-M., Deleersnijder, E., Fichefet, T., Mathieu, P.-P., Morales Maqueda, M.A., Tartinville, B., 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., Campin, J.-M., Tartinville, B., 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., Renssen, H., 2001: A two-phase response of Southern Ocean to an increase in greenhouse gas concentrations. Geophysical Research Letters, 28, 3469-3473.

Goosse H., Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 2001: Decadal variability in high northern latitudes as simulated by an intermediate complexity climate model. Annals of Glaciology, 33, 525-532.

Goosse, H., Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 2002: A mechanism of decadal variability of the sea-ice volume in the Northern Hemisphere. Climate Dynamics, 19, doi 10.1007/s00382-001-0209-5, 61-83.

Goosse, H., Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 2003: Large sea-ice volume anomalies simulated in a coupled climate model. Climate Dynamics, 20, doi 10.1007/s00382-002-0290-4, 523-536.

Goosse, H., Masson-Delmotte, V., Renssen, H., Delmotte, M., Fichefet, T., Morgan, V., van Ommen, T., Khim, B.K., Stenni, B., 2004a: A late medieval warm period in the Southern Ocean as delayed response to external forcing? Geophysical Research Letters, 31, 6, doi 10.1029/2003GL019140, L06203.

Goosse, H., Renssen, H., 2004b: Exciting natural modes of variability by solar and volcanic forcing: idealized and realistic experiments. Climate Dynamics, 23, doi 10.1007/s00382-004-0424-y, 153-163.

Goosse, H., Renssen, H., 2005: A simulated reduction in Antarctic sea-ice area since 1750: implications of the long memory of the ocean. International Journal of Climatology, 25, 569-579.

Goosse, H., Crowley, T., Zorita, E., Ammann, C., Renssen, H., Driesschaert, E., 2005a: Modelling the climate of the last millennium: What causes the differences between simulations? Geophysical Research Letters, 32, doi 10.1029/2005GL22368, L06710.

Goosse, H., Renssen, H., Timmermann, A., Bradley, R.S., 2005b: Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. Quaternary Science Reviews, 24, 1345-1360.

Huybrechts, P., 2002: Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. Quaternary Science Review, 21, 203-231.

Mouchet, A., François, L.M., 1997: Sensitivity of a global oceanic carbon cycle model to the circulation and to the fate of organic matter: preliminary results. Phys. Chem. Earth, 21, 5-6, 511-516.

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

Renssen, H., Goosse, H., Fichefet, T., Campin, J.-M., 2001: The 8.2 kyr BP event simulated by a global atmosphere-sea-ice-ocean model. Geophysical Research Letters, 28, 1567-1570.

Renssen, H., Goosse, H., Fichefet, T., 2002: Modeling the effect of freshwater pulses on the early Holocene climate: the influence of high-frequency climate variability. Paleoceanography, 17, 10.1029/2001PA000649.

Renssen, H., Brovkin, V., Fichefet, T., Goosse, H., 2003: Holocene climatic instability during the termination of the African Humid Period. Geophysical Research Letters, 30, 4, doi 1029/2002GL016636, 1184.

Renssen, H., Goosse, H., Fichefet, T., 2003: On the non-linear response of ocean thermohaline circulation to global deforestation. Geophysical Research Letters, 30, 2, doi 10.1029/2002GL016155, 1061.

Renssen, H., Goosse, H., Fichefet, T., 2005: Contrasting trends in North Atlantic deep-water formation in the Labrador and Nordic Seas during the Holocene. Geophysical Research Letters 32, doi 10.1029/2005GL022462, L08711.

Renssen, H., Goosse, H., Fichefet, T., Brovkin, V., Driesschaert, E., Wolk, F., 2005: Simulating the Holocene climate evolution at northern high latitudes using a coupled atmosphere-sea ice-ocean-vegetation mode. Climate Dynamics, 24, doi 10.1007/s00382-004-0485-y, 23-43.

Schaeffer, M., Selten, F.M., Goosse, H., Opsteegh, J.D., 2002: Limited predictability of regional climate change in IPCC SRES scenarios. Geophysical Research Letters, 29, 16, 10.1029/2002GL015254.

Schaeffer, M., Selten, F., Goosse, H., Opsteegh, T., 2004: On the influence of location of high-latitude ocean deep convection and Arctic sea-ice on climate change projections. Journal of Climate, 17, 22, 4316-4329.Selten, F.M., Haarsma, R.J., Opsteegh, J.D., 1999: On the mechanism of North Atlantic decadal variability. J. Clim., 12, 1956–1973.

Timmermann, A., Justino Barbosa, F., Jin, F.F., Goosse, H., 2004: Surface temperature control in the North Pacific during the last glacial maximum. Climate Dynamics, 23, doi 10.1007/s00382-004-0434-9, 353-370.

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

For a list of references of applications see : http://www.knmi.nl/onderzk/CKO/ecbilt-papers.html

The McGill paleoclimate model-2

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A Scope of the model

We have developed a new coupled atmosphere-ocean-sea ice-land surface-ice sheet-terrestrial biosphere model (henceforth called The McGill Paleoclimate Model-2 (MPM-2)) for long-term climate change studies [Wang, 2005]. The MPM incorporates the seasonal cycle. Three ocean basins, the Antarctic Circumpolar Current region and the major continents are resolved. Arctic Ocean and Antarctic continent are also included in this version. The model variables are sectorially averaged across the different ocean basins and continents. There are no oceanic heat and freshwater flux adjustments in the MPM-2. The major reason for developing the MPM-2 is to investigate decadal timescale abrupt climate changes, as well as millennial and Milankovitch timescale climate variability during the Quaternary period.

B Model components

One-layer atmosphere model.
Zonally averaged ocean model.
Thermodynamic sea ice model.
Land surface model.
Dynamic ice sheet model.
Terrestrial biosphere model.

Atmosphere

Balance for heat and moisture, active surface winds [Stocker et al., 1992, Fanning, Weaver, 1996, Wang, Mysak, 2000, Petoukhov et al., 2000].
The meridional energy and moisture transports are parameterized by a combination of advection and diffusion processes [Wang, Mysak, 2000].
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, Mysak, 2000].
A parameterized solar energy disposition scheme [Wang et al., 2004].
An outgoing longwave radiation scheme from [Thompson, Warren, 1982].
Resolution: 5° in meridional direction, sectorially averaged across the different ocean basins and continents.

Ocean

Dynamics based on vorticity conservation [Wright, Stocker, 1991, Stocker, 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. Arctic Ocean is represented as a mixed layer ocean.

Sea ice model

Zero-layer thermodynamic sea ice model of [Semtner, 1976].
Sea ice concentration is predicted by the method of [Hibler, 1979].
Meridional 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 [Marshall, Clarke, 1997].
The ice flow velocity is diagnosed from the ice height.
The bedrock depression is predicted from an isostatic adjustment model of [Peltier, Marshall, 1995].

Terrestrial biosphere

Tree, grass and desert fractions are calculated by VECODE based on a continuous bioclimatic classification by [Brovkin et al., 1997].

The seasonal leaf phenology, evergreen and deciduous tree fractions are parameterized [Wang et al., 2005a].

Four terrestrial carbon pools [Brovkin et al., 2002].

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.

1 year for the terrestrial biosphere model.

C Limitations

Sea ice advection velocity is prescribed.

The full ocean carbon cycle is missing; however, the solubility pump is now included.

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 20 ka integration of the MPM-2 takes approximately 24 hours in a Linux PC with an AMD Athlon MP 2200 (2.2 GHz) Processor.

E Applications

Ice sheet-thermohaline circulation interactions during a glacial period [Wang, Mysak, 2001].

Nonlinear response of thermohaline circulation to cold climates [Wang et al., 2002].

Simulation of the last glacial inception [Wang, Mysak, 2002].

Simulation of Holocene millennial climate variability [Wang et al., 2005b].

Two climatic states and thermohaline circulation stability [Wang, 2005].

Glacial abrupt climate changes and millennial oscillations [Wang, Mysak, 2005].

F References

Antico, A., Mysak, L.A., Wang, Z., Marchal, O., 2005: The solubility pump in the McGill Paleoclimate Model-2. In preparation.

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., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., Andreev, A., 2002: Carbon cycle, Vegetation and Climate Dynamics in the Holocene: Experiments with the CLIMBER-2 Model. Global Biogeochemical Cycles, 16, 4, doi:10.1029/2001GB001662, 1139.

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

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

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

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

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

Marshall, S.J., Clarke, G.K.C., 1997: A continuum mixture model of ice stream thermomechanics in the Laurentide Ice Sheet, 1. Theory. J. Geophys. Res., 102, 20,599-20,613.

Peltier, W.R., Marshall, S., 1995: 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.

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.

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

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

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

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

Wang, Y., Mysak, L.A., Wang, Z., Brovkin, V., 2005a: The Greening of the McGill Paleoclimate Model. Part I: Improved Land Surface Scheme with Vegetation Dynamics. Climate Dynamics, 24, 469-480.

Wang, Y., Mysak, L.A., Wang, Z., Brovkin, V., 2005b: The Greening of the McGill Paleoclimate Model. Part II: Simulation of Holocene Millennial-Scale Natural Climate Changes. Climate Dynamics, 24, 481-496.

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

Wang, Z., Mysak, L.A., 2001: Ice sheet-thermohaline circulation interactions in a climate model of intermediate complexity. Journal of Oceanography, 57, 481-494, 2001.

Wang, Z., Mysak, L.A., McManus, J.F., 2002a: Response of the thermohaline circulation to cold climates. Paleoceanography, 17, doi: 10.1029/2000PA00587.

Wang, Z., Mysak, L.A., 2002b: Simulation of the last glacial inception and rapid ice sheet growth in the McGill Paleoclimate Model. Geophys. Res. Lett., 29, 23, doi: 10.1029/2002GL015120.

Wang, Z., 2005: Two climatic states and feedbacks on thermohaline circulation in an Earth system Model of Intermediate Complexity. Climate Dynamics. In press.

Wang, Z., Mysak, L.A., 2005: Glacial abrupt climate changes and millennial oscillations in a coupled climate model. In preparation.

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

The MIT Integrated Global System Model

Version May 2005

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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 model predicting land vegetation changes, land CO_2, CH_4, and N_2O, fluxes, and soil composition, which feed back to the coupled chemistry/climate model. A description of the integrated model, as of 1998, can be found in [Prinn et al., 1999]. The main changes since then are that the terrestrial ecosystems model, the land model, and the natural emissions models have been consolidated and upgraded into the terrestrial model, and that the two-dimensional (2D) ocean model has been replaced by a three-dimensional (3D) ocean model. The description of the present version of the MIT IGSM is given at [Sokolov et al., 2005]. 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 model.

Model of Anthropogenic Emissions

The world economy is modeled as 16 regions, with 7 non-energy sectors, and 15 energy supply sectors in each region [Paltsev et al., 2005]. The base year for the model is 1997, and it solves at 5 year intervals from 2000 through 2100. It projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF6) and other air pollutants (CO, VOC, NOx, SO_2, NH_3, black carbon, and organic carbon) from combustion of fuels, industrial processes, waste handling, and agricultural activities. The post-processor provides estimates of emissions on a 1^ox1^o latitude-longitude grid as needed [Webster et al., 2002]. 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. The model formulation supports 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. The EPPA model structure provides the flexibility to create more finely resolved versions of the model for special studies. Examples include finer geographical detail to study European climate policy and greater agriculture sector detail to study the economic effects of changes in crop productivity due to climate change and exposure to tropospheric ozone.

Climate Model

This model couples a 2D land-ocean-resolving (LO) statistical-dynamical model of the atmosphere [Sokolov, Stone, 1998] to a 3D ocean general circulation model (GCM). 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 wave 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 four degree resolution in latitude and 11 levels in the vertical. The atmospheric model's climate sensitivity can be changed by varying the cloud feedback. The atmospheric model has been coupled to an ocean GCM which uses the MOM2 code developed at the Geophysical Fluid Dynamics Laboratory and a simplified global geometry [Kamenkovich et al., 2002]. More recently the atmospheric model has been coupled to an ocean GCM which uses the code developed at MIT [Marshall et al., 1997] and has a realistic bathymetry [Dutkiewicz et al., 2005]. In both ocean GCMs the resolution is 4 degrees in the horizontal with 15 layers in the vertical. Mesoscale eddies are represented by the Gent-McWilliams parameterization. The latest version includes a thermodynamic sea-ice model based on the 3-level model of [Winton, 2000] and the LANL CICE model [Bitz, Lipscome, 1999]. An earlier version of the climate model which used a zonally averaged mixed-layer diffusive ocean [Sokolov, Stone, 1998] in place of the ocean GCM was modified by replacing the zonally averaged representation with a 2D (longitude/latitude) representation and this latter version is still used for many studies. Both the mixed-layer diffusive ocean and the ocean GCM with the MIT code contain a carbon cycle.

Atmospheric Chemistry Model

To calculate atmospheric composition, the model of atmospheric chemistry includes an analysis of the climate-relevant reactive gases and aerosols at urban scales, coupled to a 2D zonal mean model to predict the atmospheric composition in non-urban areas including exported pollutants from urban areas. The 2D zonal mean model includes 33 chemical species. The continuity equations for various chemical species and sulfate as well as carbonaceous aerosols include convergences due to transport, parameterized north-south eddy transport, convective transports, local true production or loss due to surface emission or deposition, and 41 gas-phase and 12 heterogeneous atmospheric chemical reactions [Wang et al., 1998]. The scavenging of carbonaceous and sulfate aerosol species by precipitation are also included using method derived based on a 3D climate-aerosol-chemistry model [Wang, 2004]. The sub-grid fast urban chemistry module is a reduced format model derived based on the detailed 3D California Institute of Technology (CIT) Urban Air-shed Model [Mayer et al., 2000]. Urban air-shed conditions are resolved at low, medium and high levels of pollution. The reduced-form urban air chemistry model also provides detailed information about particulates and their precursors. In climate-chemistry coupling at each model time step, the climate model provides wind speeds, temperature, solar radiation flux and precipitation, which are used in the chemistry formulation. Predicted radiatively important species including aerosols by the chemistry model are then used in climate model to calculate radiative fluxes.

Terrestrial Model

The terrestrial component of the IGSM includes dynamically linked hydrologic and ecologic models. Hydrologic processes and surface-heat fluxes are represented by the Community Land Model [CLM, Bonan, 2002]. CLM is based upon the Common Land Model [Zeng et al., 2002] that was derived from a multi-institutional collaboration of land models, and carefully tested [Dai et al., 2003]. CLM is used in global-scale land data assimilation research [e.g. Rodell et al., 2004] as well as coupled climate prediction studies [e.g. Dai et al., 2004, Duffy et al., 2003, Govindasamy et al., 2003, Holland, 2003]. CLM is dynamically linked to the Terrestrial Ecosystems Model (TEM) of the Marine Biological Laboratory [Melillo et al., 1993, Xiao et al., 1997, 1998, Zhang et al., 2004], which simulates the carbon dynamics of terrestrial ecosystems. Further, methane and nitrogen exchange are considered through the Natural Emissions Model [NEM, Liu 1996], which is driven by dynamic inputs from both TEM and CLM. This version also incorporates the influence of ozone on plant productivity [Felzer et al., 2004] and the influence of soil thermal regime on terrestrial carbon and nitrogen dynamics [Zhuang et al., 2003]. The coupled CLM/TEM/NEM model system represents the geographical distribution of global land cover and plant diversity through a mosaic approach, in which all major land cover types and plant functional types are considered over given domain (i.e. model grid box), and are area-weighted to obtain aggregate fluxes and storages.

Miscellaneous

The integrated model also calculates the contributions to sea-level rise due to the thermal expansion of the oceans and the melting of the world's mountain glaciers. The latter is calculated using an algorithm which relates the melting to changes in global mean temperature, based on results from coupled GCMs, which are quite robust. The contributions from changes in the Greenland and Antarctic ice sheets are neglected.

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 3.0 GHz Pentium 4 CPU: A 100 year simulation with the climate model using the MIT ocean GCM requires 16 hours; with the coupled climate-chemistry-ocean GCM with carbon cycle model-Nem it requires 36 hours. The other component models have minimal computer requirements.

Memory usage: 80 MB for the climate only model ; 140 MB for the full model.

E Applications

Analysis of the Kyoto Protocol (Reilly et al., 1999].
Constraining uncertainties in climate model characteristics [Forest et al., 2000, 2001, 2002, Sokolov et al., 2003].
Simulations of changes in the thermohaline circulation in global warming scenarios [Kamenkovich et al., 2005].
Simulations of ecosystem changes in global warming scenarios [Xiao et al., 1997, 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, Webster et al., 2003].

F References

Bitz, C.M., Lipscome, W.H., 1999: An energy conserving thermodynamic model of sea ice. J. Geophys. Res., 104, 15.669-15677.

Bonan, G.B., Oleson, K.W., Vertenstein, M., Lewis, S., Zeng, X., Dai, Y., Dickinson, R.E., Yang, Z.-L., 2002: The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model. J. Climate, 15, 3123-3149.

Dai, A., Washington, W.M., Meehl, G.A., Bettge, T.W., Strand, W.G., 2004: The ACPI climate change simulations. Climatic Change, 62, 29-43.

Dai, Y., Zeng, X., Dickinson, R.E., Baker, I., Bonan, G., Bosilovich, M., Denning, S., Dirmeyer, P., Houser, *P., Niu, G., Oleson, K., Schlosser, A., Yang, Z.-L., 2003: The Common Land Model (CLM). Bull. Amer. Meteor. Soc., 84, 1013-1023.

Duffy, P.B., Govindasamy, B., Iorio, J.P., Milovich, J., Sperber, K.B., Taylor, K.E., Wehner, M.F., Thompson, S.L., 2003: High resolution simulations of global climate, Part 1: Present climate. Clim. Dyn., 21, 371-390.

Dutkiewicz, S., Sokolov, A., Scott, J., Stone, P., 2005: A Three-Dimensional Ocean-Seaice-Carbon Cycle Model and its Coupling to a Two-Dimensional Atmospheric Model: Uses in Climate Change Studies. Report No. 122, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA.

Felzer, B., Kicklighter, D.W., Melillo, J.M., Wang, C., Zhuang, Q., Prinn, R., 2004: Ozone effects on net primary production and carbon sequestration in the conterminous United States using a Biogeochemistry Model. Tellus, 56B, 230-248.

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

Forest, C.E., Allen, M.R., Sokolov, A.P., Stone, P.H., 2001: Constraining climate model properties using optimal fingerprint detection methods. Climate Dyn., 18, 277-295.

Forest, C.E., Stone, P.H., Sokolov, A.P., Allen, M.R., Webster, M., 2002: Quantifying uncertainties in climate system properties with the use of recent climate observations. Science, 295, 113-117.

Govindasamy, B., Duffy, P.B., Coquard, J., 2003: High-resolution simulations of global climate, Part 2: Effects of increased greenhouse gases. Clim. Dyn., 21, 391-404.

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

Holland, M.M., 2003: The North Atlantic Oscillation/Arctic Oscillation in the CCSM2 and its influence on Arctic climate variability. J. Climate, 16, 2767-2781.

Kamenkovich, I.V., Sokolov, A., Stone, P.H., 2002: A coupled atmosphere-ocean model of intermediate complexity for climate change study. Climate Dyn, 85, 598.

Kamenkovich, I.V., Sokolov, A., Stone, P.H., 2003: Feedbacks affecting the response of the thermohaline circulation to increasing CO_2: a study with a model of intermediate complexity. Climate Dynamics, 21, doi: 10.1007/s00382-003-0325-5, 119-130.

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.

Marshall, J.C., Hill, C., Perelman, L., Adcroft, A., 1997: Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling. J. Geophys. Res., 102, 5733-5752.

Mayer, M., Wang, C., Webster, M., Prinn, R.G., 2000: Linking local air pollution eo global chemistry and climate. J. Geophys. Res., 105, D18, 22869-22896.

Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore III, B., Vorosmarty, C.J., Schloss, A.L., 1993: Global climate change and terrestrial net primary production. Nature, 363, 234-240.

Paltsev, S., Jacoby, H., Reilly, J., Viguier, L., Babiker, M., 2005: Modeling the Transport Sector: The Role of Existing Fuel Taxes in Climate Policy. In: Energy and Environment, Loulou, R., Waaub, J.-P., Zaccour, G. (eds.), Springer.

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

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

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004: The Global Land Data Assimilation System. Bull. Amer. Meteor. Soc., 85, 3, 381-394.

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

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

Sokolov, A., Forest, C.E., Stone, P.H., 2003: Comparing oceanic heat uptake in AOGCM tansient climate change experiments. J. Climate, 16, 1573-1582.

Sokolov, A.P., Schlosser, C.A., Dutkiewicz, S., Jacoby, H.D., Kicklighter, D.W., Prinn, R., Forest, C.E., Paltsev, S., Reilly, J., Sarofim, M.C., Scott, J., Stone, P., Wang, C., 2005: The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation. Report No. 125, Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA.

Wang, C., 2004: A modeling study on the climate impacts of black carbon aerosols. J. Geophys. Res., 109, doi:10.1029/2003JD004084, D03106.

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

Webster, M., Babiker, M., Mayer, M., Reilly, J., Harnisch, J., Hyman, R., Sarofim, M., Wang, C., 2002: Uncertainty in emissions projections for climate models. Atmospheric Environment, 36, 3659-3670.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, Sarofim, M., Sokolov, A., Stone, P., Wang, C., 2003: Uncertainty analysis of climate change and policy response. Climatic Change, 62, 295-320.

Winton, M., 2000: A reformulated three-layer sea ice model. J. Atmos. and Ocean Tech., 17, 525-531.

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

Zeng, X., Shaikh, M., Dai, Y., Dickinson, R.E., Myneni, R., 2002: Coupling of the Common Land Model to the NCAR Community Climate Model. J. Climate, 15, 1832-1854.

Zhaung, Q., McGuire, A.D., Melillo, J.M., Clein, J.S., Dargaville, R.J., Kicklighter, D.W., Myneni, R.B., Dong, J., Romanovsky, V.E., Harden, J., Hobbie, J.E., 2003: Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th Century: A modeling analysis of the influences of soil thermal dynamics. Tellus, 55B, 751-776.

Zhuang, Q., Melillo, J.M., Kicklighter, D.W., Prinn, R.G., McGuire, D.A., Steudler, P.A., Felzer, B.S., Hu, S., 2004: Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model. Global Biogeochemical Cycles 18, GB3010, doi:10.1029/2004GB002239.

The MoBidiC Climate Model

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A Scope of the model

The MoBidiC model is based on the LLN-2D sectorial model [Gallée et al., 1991]. This first model 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, Crucifix et al., 2001a]. The effect of CO_2 concentration variations on climate were also analysed [Berger et al., 1998, Loutre, 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., 2002a]. 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. Recently published applications include transient simulations over the Eemian, the Holocene and the deglaciation. Simulations on future climate are also performed with MoBidiC (cf. "E" for a full list).

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.
ice-sheet evolution and isostatic rebound.

Atmosphere dynamics [Gallée et al., 1991a] + updates in [Crucifix et al., 2002a]

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].
advection velocity prescribed.
leads and white ice.

Ocean [Hovine et al., 1994] + updates in [Crucifix et al., 2001b, 2002c]

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"(i.e. convection is achieved by prescribing a very large vertical diffusivity in unstable columns).

Parameterization of downsloping current.

Vertical resolution : 15 levels unequally spaced.

Latitudinal resolution : 5 degrees.

Ocean carbon cycle [Crucifix, Joos, 2004]

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.

Export production partitioned between POC and DOC.

Carbonate cycling but no storage in the sediment.

Ice sheets [Gallée et al., 1992] + updates in [Dutrieux, 1998, Crucifix et al., 2001a]

Vertically integrated model (ice mass conservation) of the ice sheets of North America, Greenland and Eurasia, and Eastern and Western Antarctica.

The ice sheet thickness is predicted by an ice mass conservation equation.

Lateral mass discharge is computed assuming that each ice sheet behaves along the longitude in a perfect plastic manner.

Meltwater flow and iceberg calving are explicitly calculated.

The deflection of bedrock is approximated using the local damped isostasy model with effective asthenosphere density and relaxation time.

Time steps

2 days for ocean and atmosphere dynamics.

2 days for ocean tracers, radiative scheme, land surface and hydrological cycle.

1 year for vegetation.

1 year for ice sheet.

seasonal cycle included.

C Limitations

the zonally averaged representation of the atmosphere prevents the study of processes linked to monsoon.

processes linked to interannual and interdecadal variability are not, or poorly represented.

clouds, relative surface humidity and surface drag coefficient are prescribed.

canopy 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., van Ypersele, J.-P., Fichefet, T., Marsiat, I., Tricot, C., Berger, A., 1992: 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.

Berger, A., Tricot, C., Gallée, H., Loutre, M.F., 1993: Water vapor, CO_2 and insolation over the last glacial-interglacial cycles. Phil. Trans. R. Soc. Lond. B, 341, 253-261.

Berger, A., Loutre, M.F., Gallée, H., 1998: Sensitivity of the LLN climate model to the astronomical and CO_2 forcing over the last 200 kyr. Climate Dynamics, 14, 615-629.

Berger, A., 1999: 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.

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

Berger, A., Loutre, M.F., 2003: Climate 400,000 years ago, a key to the future? In : Earth's Climate and Orbital Eccentricity. The marine isotope stage 11 question. Droxler, A.W., Poore, R.Z., Burckle, L.H. (eds). Geophysical Monograph, 137. AGU, Washington, DC, 17-26, 2003.

Berger, A., Loutre, M.F., Crucifix, M., 2003: The earth's climate in the next hundred thousand years (100 kyr). Surveys of Geophysics, 24, 117-138.

Brovkin, V., Claussen, M., Driesschaert, E., Fichefet, T., Kicklighter, D., Loutre, M.F., Matthews, H.D., Ramankutty, N., Schaeffer, M., Sokolov, A.: Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. Submitted.

Crucifix, M., Loutre, M.F., Lambeck, K., Berger, A., 2001a: Effect of isostatic rebound on modelled ice volume variations during the last 200 kyr. Earth and Planetary Science Letters, 184, 3-4, 623-633.

Loutre, M.F., Berger, A., 2000: No glacial-interglacial cycle in the ice volume simulated under a constant astronomical forcing and a variable CO_2. Geophys. Res. Lett., 27, 6, 783-786.

Loutre, M.F., Berger, A., 2000: Future climatic changes: Are we entering an exceptionally long interglacial? Climate Change, 46, 1-2, 61-90.

Loutre, M.F., 2003: Clues from MIS11 to predict the future climate-a modelling point of view. Earth and Planetary Science Letters, 212, doi:10.1016/S0012-821X(03)00235-8, 213-224.

Loutre, M.F., Berger, A., 2003: Stage 11 as an analogue for the present interglacial. Global and Planetary Change, 36, 3, doi 10.1016/S0921-8181(02)00186-8, 209-217.

with MoBidiC

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

Bertrand, C., Loutre, M.F., Crucifix, M., Berger, A., 2002: Climate of the Last millennium: a sensititvity study. Tellus, 54(A), 221-244.

Brovkin, V., Levis, S., Loutre, M.F., Crucifix, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., 2003: Stability Analysis of the Climate-Vegetation System in the Northern High Latitudes. Climatic Change, 57, 1, 119-138.Crucifix, M., Tulkens, P., Berger, A., 2001b: Modelling abrupt events in glacial climate. In: The Oceans and Rapid Climate Changes: Past, Present and future. Haupt, B. J., Maslin, M.A. (eds). AGU Monograph Series, 117-134.

Crucifix, M., Loutre, M.F., Tulkens, P., Fichefet, T. Berger, A., 2002a: Climate evolution during the Holocene: a study with an Earth system model of intermediate complexity. Clim. Dyn., 19, 43-60.

Crucifix, M., Loutre, M.F., 2002b: Transient simulations over the last interglacial period (126-115 kyr BP): feedback and forcing analysis. Climate Dynamics, 19, doi 10.1007/s00382-002-0234-z, 417-433.

Crucifix, M., Berger, A., 2002c: Simulation of ocean-ice sheet interactions during the last deglaciation. Paleoceanography, 17, 4, doi 10.1029/2001PA000702, 1054.

F References on model description

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

Crucifix, M., Loutre, M.F., Lambeck, K., Berger, A., 2001c: Effect of isostatic rebound on modelled ice volume variations during the last 200 kyr. Earth and Planetary Science Letters, 184, 3-4, 623-633.

Crucifix, M., Loutre, M.F., Tulkens, P., Fichefet, T., Berger, A., 2002a: Climate evolution during the Holocene: a study with an Earth system model of intermediate complexity. Climate Dynamics, 19, 1, 43-60.

Crucifix, M., Berger, A., 2002c: Simulation of ocean-ice sheet interactions during the last deglaciation. Paleoceanography, 17, 4, doi 10.1029/2001PA000702, 1054.

Crucifix, M., Joos, F., 2004: Carbon isotopes in the glacial ocean: a model study. Scientific Report 1/2004, Institut d'Astronomie et de Géophysique G. Lemaître, Université catholique de Louvain.

Dutrieux, A., 1997: Etude des variations à long terme du climat à l'aide d'un modèle global à deux dimensions du système climatique. In: Institut d'Astronomie et de Géophysique G. Lemaître, Université catholique de Louvain, Louvain-la-Neuve, pp. 274.

Gallée, H., van Ypersele, J.-P., Fichefet, T., Tricot, C., Berger, A., 1991: 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.

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

Hovine, S., Fichefet, T., 1994: A zonally averaged, three basin ocean-circulation model for climate studies. Clim. Dyn, 10, 313-331.

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

Tulkens, P., 1998: 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.

Planet Simulator

Version May 2005

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A Scope of the model

The **Planet-Simulator** is a MIC (**M**odel of **I**ntermediate **C**omplexity) which can be used to run paleo- and climate-simulations for time scales up to 10 thousand years or more in an acceptable real time. The priorities in development were set to speed, user friendliness and portability. Its modular structure allows a problem dependant configuration. There exist also applications for the Martian atmosphere [Segschneider et al., 2004] and the atmosphere of the Saturn moon Titan [Grieger et al., 2005]. A coupling interface enables the addition of ocean models, ice models, vegetation etc.. A graphical "Model Starter" (Figure 1) can be used for easy and fast setup and configuration. An interactive mode with a **G**raphical **U**ser **I**nterface (Figure 2) can be used to view atmospheric fields while changing model parameters on the fly. This is especially useful for teaching, debugging and tuning of parameterizations.

B Model components

Atmosphere

The atmospheric module of the Planet Simulator is PUMA-2 (**P**ortable **U**niversity **M**odel of the **A**tmosphere), developed from PUMA [Fraedrich et. al., 1998]. PUMA-2 is a spectral model with triangular truncation. It solves the moist Primitive Equations on σ-coordinates in the vertical. Resolutions range from T21 and five levels for very fast running simulations to T42 and ten levels for a more realistic or detailed simulation, though other resolutions are also available. Included are boundary layer, precipitation, interactive clouds and radiation.

Ocean

A mixed layer ocean (ML) is included in the Planet Simulator. An interface for coupling of the full ocean models LSG and UVIC is in preparation.

Sea ice

Thermodynamic sea ice model.

Terrestrial Biosphere

Simulator of Biospheric Aspects (SimBA, Kleidon).
Temperature, surface wetness and radiation control biomass und vegetation cover.

Miscellaneous

The Planet Simulator is designed for high flexibility in order to simulate also other planets or moons with atmospheres. Successful simulations were done recently by [Segschneider et. al., 2004] for the planet Mars and by [Grieger et. al., 2005] for the Saturn moon Titan.

C Limitations

The model has the typical problems of all spectral models, like the Gibb's phenomenon visible in the orography and the necessary correction of gridpoints with negative humidity. The parametrizations are optimized for speed and efficiency as typical for EMIC models.

D Performance

Due to the high portability the Planet Simulator can be run on a wide range of computers ranging from mainframes to PC's. It is fully parallelized and can be run on as many CPUs as latitudes (32 for the standard T21 resolution). On a PC with a single Pentium-IV Processor at 3GHz the Planet Simulator in standard configuration runs one year of simulation in 10 minutes wall clock time. Using a PC with two CPUs speeds up the program at a factor 1.8 - 1.9 such using about 5 minutes per simulation year.

E Applications

Simulation of the Martian atmosphere.
Simulation of Titan's atmosphere.
Paleosimulation of the Earth.

F References

Fraedrich, K., Jansen, H., Kirk, E., Luksch, U., Lunkeit, F., 2005: The Planet Simulator: Towards a user friendly model. Meteorol. Z., 14, 299-304.

Fraedrich, K., Jansen, H., Kirk, E., Lunkeit, F., 2005: The Planet Simulator: Green planet and desert world. Meteorol. Z., 14, 305-314.

Grieger, B., Segschneider, J., Keller, H.U., Rodin, A.V., Lunkeit, F., Kirk, E., Fraedrich, K., 2005: Simulating Titan's tropospheric circulation with the Portable University Model of the Atmosphere. Advances in Space Research. In press.

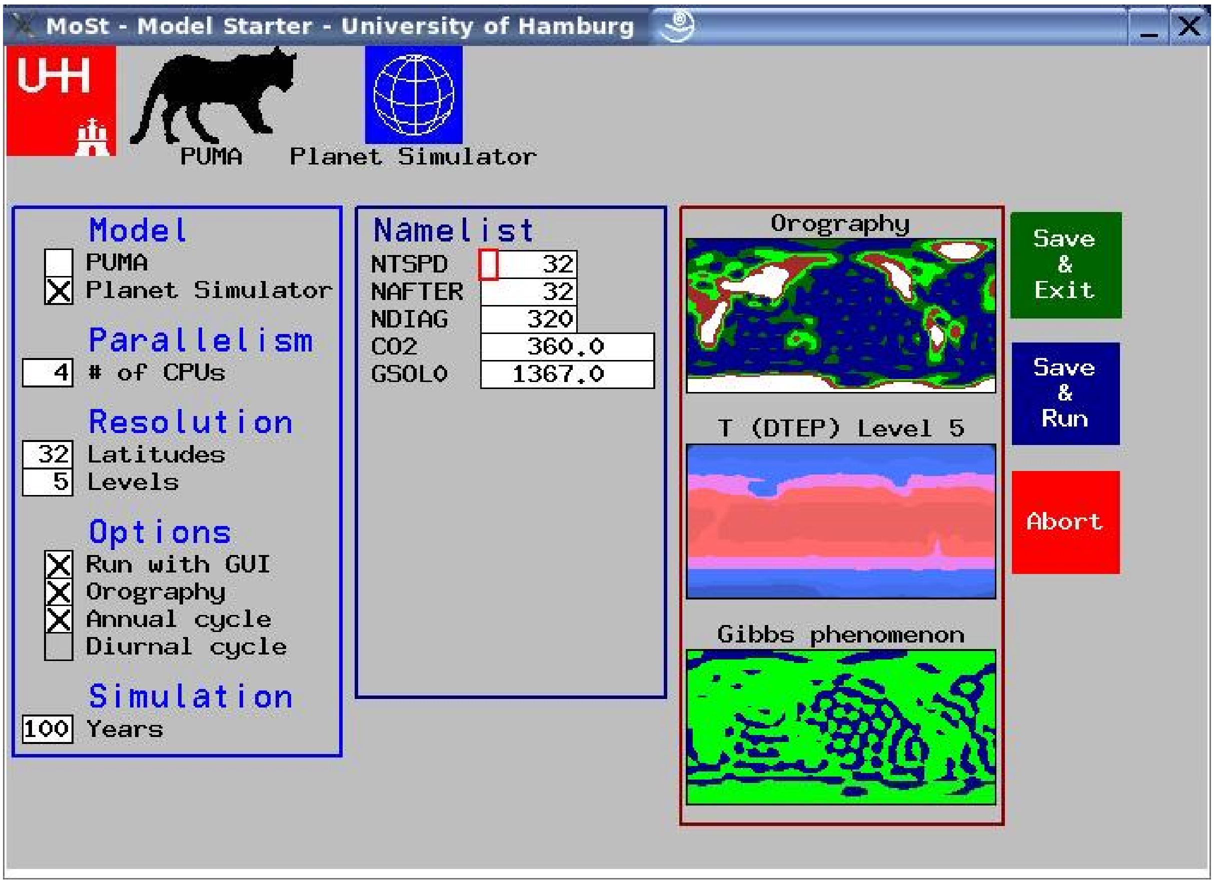
Grosfeld, K., Lohmann, G., Rimbu, N., Lunkeit, F., Fraedrich, K., 2005: North Atlantic Atmospheric Response to Multidecadal Sea Surface Temperature Variability: Observations, Models and Proxy Data. Tellus. Submitted.

Knorr, G.K., Grosfeld, G., Lohmann, G., Lunkeit, F., Fraedrich, K., 2005: Atmospheric responses to abrupt changes in the thermohaline circulation during deglaciation. Geochemistry, Geophysics, Geosystem. Submitted.

Lunkeit, F., Blessing, S., Fraedrich, K., Jansen, H., Kirk, E., Luksch, U., Sielmann, S., 2005: Planet Simulator User's Guide (http://www.mi.uni-hamburg.de/plasim).

Lunkeit, F., Böttinger, M., Fraedrich, K., Jansen, H., Kirk, E., Kleidon, A., Luksch, U., 2005: Planet Simulator Reference Manual (http://www.mi.uni-hamburg.de/plasim).

Segschneider, J., Grieger, B., Keller, H.U., Lunkeit, F., Kirk, E., Fraedrich, K., Rhodin, A., Greve, R., 2005: Response of the intermediate complexity Mars Climate Simulator to different obliquity angles. Planetary and Space Science, 53, 659-670.



Model

☐ PUMA
☒ Planet Simulator

Parallelism

4 # of CPUs

Resolution

32 Latitudes
5 Levels

Options

☒ Run with GUI
☒ Orography
☒ Annual cycle
☐ Diurnal cycle

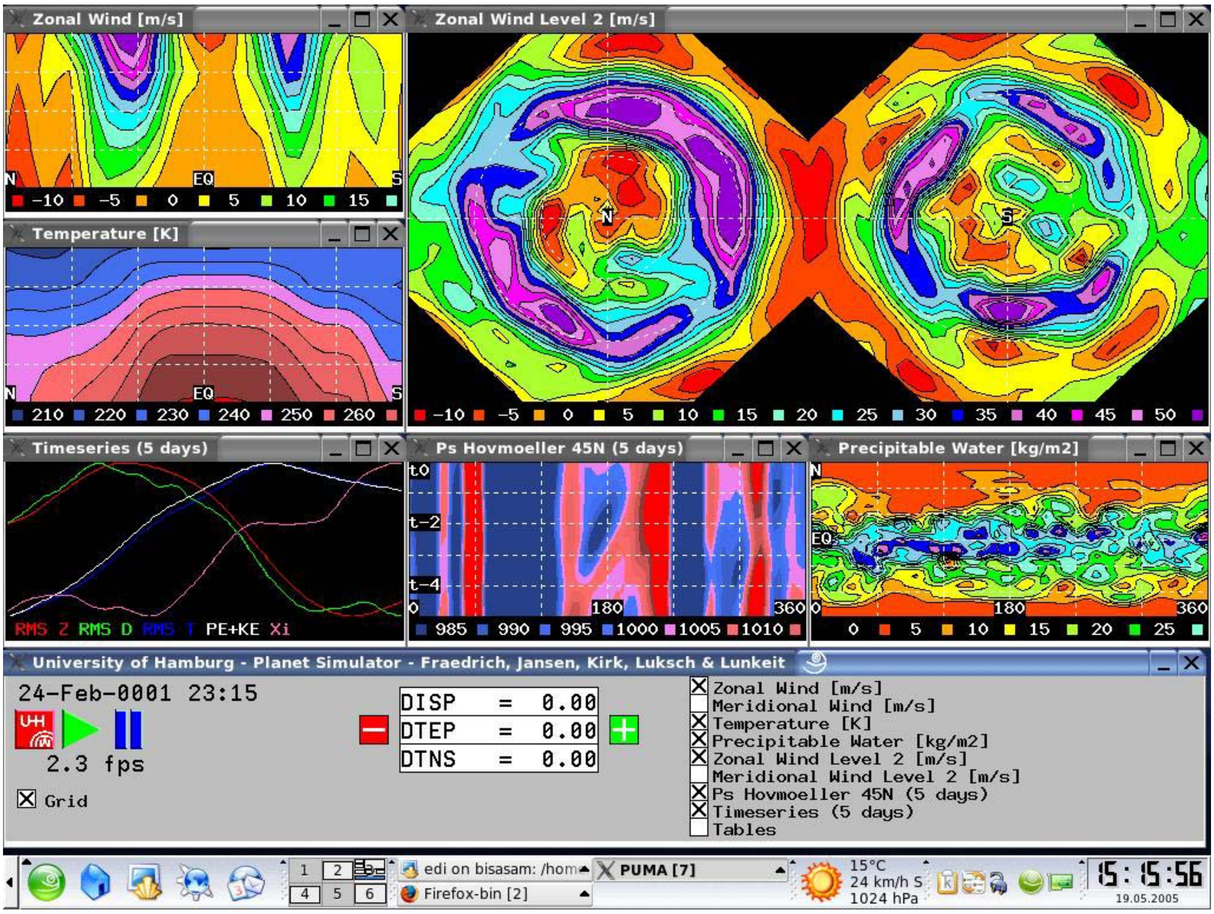
Simulation

100 Years

Namelist

NTSPD 32
NAFTER 32
NDIAG 320
CO2 360.0
GSOL0 1367.0

Figure 1: Screenshot of the Model Starter for PUMA and Planet Simulator



24-Feb-0001 23:15

2.3 fps

☒ Grid

DISP = 0.00
DTEP = 0.00
DTNS = 0.00

☒ Zonal Wind [m/s]
☐ Meridional Wind [m/s]
☒ Temperature [K]
☒ Precipitable Water [kg/m2]
☒ Zonal Wind Level 2 [m/s]
☐ Meridional Wind Level 2 [m/s]
☒ Ps Hovmoeller 45N (5 days)
☒ Timeseries (5 days)
☐ Tables

Figure 2: Screenshot of the Graphical User Interface for PUMA and Planet Simulator

PUMA

Version May 2005

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A Scope of the model

PUMA (**P**ortable **U**niversity **M**odel of the **A**tmosphere) is a very fast dynamical core of an atmospheric model. It can be used to run simulations on long time scales and inexpensive hardware. The priorities in development were set to speed, easy handling, portability and well documented coding. The compatibility of PUMA to the Planet Simulator and ECHAM makes it an ideal tool to teach modelling to junior scientist and students. An interactive mode with a GUI (**G**raphical **U**ser **I**nterface) can be used to view atmospheric fields while changing model parameters on the fly. This is especially useful for teaching, debugging and tuning of parameterizations.

B Model components

Atmosphere

PUMA is a spectral model with triangular truncation. It solves the Primitive Equations on σ-coordinates in the vertical. Possible horizontal resolutions are T21, T31, T42, and T85. The vertical resolution is an arbitrary number of levels. The parameterisations are Rayleigh friction and Newtonian cooling.

Miscellaneous

PUMA is a model of the atmosphere and is usually run without orography as an "Aqua Planet". It is however possible to include orography (realistic or synthetic) in the model. Due to its small code size of less than 4000 FORTRAN lines (without GUI and MPI) PUMA is an ideal teaching tool for courses in atmospheric modeling. An adjoint version of PUMA is under development.

C Limitations

The model has the typical problems of all spectral models, like the Gibbs phenomenon. It simulates the dry atmosphere with only few necessary parameterisations like Rayleigh friction and Newtonian cooling. There are no moist processes and no boundary layer.

D Performance

Due to the high portability PUMA can be run on a wide range of computers ranging from mainframes to PC's. It is fully parallelized and can be run on as many CPUs as latitudes (32 for the standard T21 resolution). On a PC with a single Pentium-IV Processor at 3GHz PUMA in standard configuration runs one year of simulation in 2 minutes wall clock time. Using a PC with two CPUs speeds up the program by a factor 1.8 - 1.9 using about 1 minute per simulation year.

E Applications

Simulation of stormtracks.
Lagrangian tracers.
Stochastic forcing.
Synchronization experiments.
Maximum entropy production.
Stratosphere–troposphere interaction.

F References

Bagliani, M., Fraedrich, K., von Hardenberg, J., Lunkeit, F., Provencale, A., 2000: Lagrangian tracer homogenization and dispersion in a simplified atmospheric GCM. Il Nuovo Cimento, 23C, 433-448.

Blessing, S., Fraedrich, K., Lunkeit, F., 2004: The Climate in Historical Times. Towards a Synthesis of Holocene Proxy Data and Climate Models. Miller, H., Negendank, J.F.W., Flöser, G., von Storch, H., Fischer, H., Lohmann, G., Kumke, T. (eds.). GKSS School of Environmental Research, Springer-Verlag, 383-396.

Fraedrich, K., Kirk, E., Lunkeit, F., 1998: Portable University Model of the Atmosphere. DKRZ Report, 16 (http://www.mad.zmaw.de/Pingo/reports/ReportNo.16.pdf).

Fraedrich, K., Kirk, E., Luksch, U., Lunkeit, F., 2003: Ein Zirkulationsmodell für Forschung und Lehre. Promet, 29, 34-48.

Fraedrich, K., Kirk, E., Luksch, U., Lunkeit, F., 2005: The Portable University Model of the Atmosphere (PUMA): Storm track dynamics and low frequency variability. Meteorol. Z., 14.

Franzke, C., Fraedrich, K., Lunkeit, F., 2000: Low frequency variability in a simplified atmospheric global circulation model: Storm track induced 'spatial resonance'. Q. J. R. Meteorol. Soc., 126, 2691-2708.

Franzke, C., Fraedrich, K., Lunkeit, F., 2001: Teleconnections and low frequency variability in idealised experiments with two storm tracks. Q. J. R. Meterol. Soc., 127, 1321-1339.

Frisius, T., Lunkeit, F., Fraedrich, K., James, I.A., 1998: Storm-track organization and variability in a simplified atmospheric global circulation model (SGCM). Q. J. R. Meteorol. Soc., 124, 1019-1043.

Grieger, B., Segschneider, J., Keller, H.U., Rodin, A.V., Lunkeit, F., Kirk, E., Fraedrich, K., 2003: Simulating Titan's tropospheric circulation with the Portable University Model of the Atmosphere. Advances in Space Research. In press.

James, P.M., Fraedrich, K., James, I.N., 1994: Wave-zonal flow interaction and ultra-low frequency variability in a simplified general circulation model. Q. J. R. Meteorol. Soc., 120, 1045-1067.

Kleidon, A., Fraedrich, K., Kunz, T., Lunkeit, F., 2003: The atmospheric circulation and states of maximum entropy production. Geophys. Res. Letters, 30, 23, 9-(1-4).

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

Lunkeit, F., 2001: Synchronization experiments with an atmospheric global circulation model. Chaos, 11, 47-51.

Müller, W., Blender, R., Fraedrich, K., 2002: Low frequency variability in idealised GCM experiments with circumpolar and localised storm tracks. Nonlinear Processes Geophys., 9, 37-49.

Pérez-Munuzuri, V., Lorenzo, M.,N., Montero, P., Fraedrich, K., Kirk, E., Lunkeit, F., 2004: Spatio-temporal stochastic forcing of an ensemble of global circulation models. Nonlinear Processes Geophys., 10, 453-46.

Stenzel, O.J., von Storch, J.-S., 2004: On the effect of the thermal forcing on the global AAM circulation. Climate Dynamics, 22, 415-427.

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

Walter, K., Luksch, U., Fraedrich, K., 2001: A response climatology of idealised midlatitude SST anomaly experiments with and without stormtrack. J. Climate, 14, 467-484.

The UVic Earth System Climate Model

Version 2.7

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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, a thermomechanical land ice model, a dynamic terrestrial vegetation model and a terrestrial and ocean carbon cycle model. The philosophy underlying the development of the UVic ESCM is that on timescales greater than a decade, the ocean, its horizontal gyre structure, and its ability to transport heat and freshwater are key components of the climate system. As such, the model has been built to resolve as many processes and feedbacks as possible that affect climate sensitivity and oceanic heat uptake on long timescales. It is also constructed in a modular fashion so that only a subset of processes or subcomponent models may be included, depending on the particular scientific question of concern. The model is described in [Weaver et al , 2001] and is publicly available (upon request) from http://climate.uvic.ca/model.

B Model components

Atmospheric model

The atmospheric model is loosely based on the energy-moisture balance model of [Fanning, Weaver, 1996]. Atmospheric heat transport is parameterised as a diffusive process and freshwater transport is accomplished through advection and diffusion. Precipitation is assumed to occur when the relative humidity reaches greater than 90%. Runoff from land returns to the ocean via one of 33 observed river drainage basins. Ice, snow and vegetation albedo feedbacks are included in the coupled model through changes to the surface albedo. The EMBM includes a parameterisation of the water vapour/planetary longwave feedback [Thompson, 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 an 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 rheology of [Hunke, 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].

Ice sheet model

The UBC thermomechanical ice sheet model of [Marshall, Clarke, 1997] is included in the model.

Ocean chemistry

A full ocean carbon cycle model (including ocean biota) has been incorporated. OCMIP guidelines were used for chemistry and a modified NPZD model from [Giraud et al., 2000] was used to represent biology.

Vegetation/land surface components

Two land surface schemes may be used. The first is a simple bucket model which requires the specification of vegetation type for calculating surface albedo. The second is a one-layer model representing a simplified version of the Hadley Centre MOSES2 scheme [Cox et al., 1999] coupled to the Hadley Center vegetation model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) [Cox et al. 2000, 2001], in which vegetation change is driven by net carbon fluxes.

Other developments

Our code is currently being optimised for use on the NEC SX6 architecture.

C Limitations

The single biggest weakness of the UVic model is its simplified representation of the atmosphere. However, this is also a strength as it allows for easier diagnostic analysis of climate feedbacks. Cloud feedbacks are not currently incorporated directly, although simple parametrisations for these are being developed. Internal tropical variability is not captured.

References cited above:

Cox, P,M., Betts, R.A., Bunton, C.B., Essery, R.L.H., Rowntree, P.R., Smith, J., 1999: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. Clim Dyn, 15, 183-203.

Cox, P.M., Betts, R., Jones, C., Spall, S., Totterdell, I., 2000: Acceleration of global warming due to carbon-cycle feed-backs in a coupled climate model. Nature, 408, 184-187.

Cox, P.M., 2001: Description of the "TRIFFID" Dynamic Global Vegetation Model. Hadley Centre, Technical Note, 24.

Giraud, X., Bertrand, P., Garçon, V., Dadou, I., 2000: Modeling ∂^{15}N evolution: First palaeoceanographic applications in a coastal upwelling system. J. Mar. Res., 58, 609-630(22).

Hibler III, W.D., 1979: A dynamic thermodynamic sea ice model. J Phys Oceanogr 9, 4, 815-846.

Hunke, E.C., Dukowicz, J.K., 1997: An elastic-viscous-plastic model for sea ice dynamics. J Phys Oceanogr, 27, 9, 1849-1867.

Marshall, S.J., Clarke, G.K.C., 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., Warren, S.G., 1982: Parameterization of outgoing infrared radiation derived from detailed radiative calculations. J. Atmos. Sci., 39, 2667-2680.

D Performance

Current Speed of Model:

From 200-1100 -years (depending on options) per CPU day on a Pentium 4.

E Applications

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

Bitz, C.M., Holland, M.M., Weaver, A.J., Eby, M., 2001: Simulating the ice-thickness distribution in a coupled climate model. Journal of Geophysical Research, 106, 2441-2463.

Cottet-Puinel, M., Weaver, A.J., Hillaire-Marcel, C., de Vernal, A., Clark, P.U., Eby, M., 2004: Variation of Labrador Sea water formation over the last glacial cycle in a climate model of intermediate complexity. Quaternary Science Reviews, 23, 449–465.

Duffy, P.B., Eby, M., Weaver, A.J., 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.

Duffy, P.B., Eby, M., Weaver, A.J., 2001: Climate model simulations of effects of increased atmospheric CO_2 and loss of sea ice on ocean salinity and tracer uptake. Journal of Climate, 14, 520-532.

Ewen, T., Weaver, A.J., Schmittner, A., 2004: Modelling carbon cycle feedbacks during abrupt climate change. Quaternary Science Reviews, 23, 431-448.

Ewen, T.L., Weaver, A.J., Eby, M., 2004: Sensitivity of the inorganic ocean carbon cycle to future climate warming in the UVic coupled model. Atmosphere-Ocean, 42, 23-42.

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

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

Gregory, J.M., Saenko, O.A., Weaver, A.J., 2003: The role of the Atlantic freshwater balance in the hysteresis of the meridional overturning circulation. Climate Dynamics, 21, 707–717.

Hickey, H., Weaver, A.J., 2004: The Southern Ocean as a source region for tropical Atlantic variability. Journal of Climate, 17, 3960–3972.

Holland, M.M., Bitz, C.M., Eby M., Weaver, A.J., 2001: The role of ice ocean interactions in the variability of the North Atlantic thermohaline circulation. Journal of Climate, 14, 656-675.

Holland, M.M., Bitz, C.M., Weaver, A.J., 2001: The influence of sea ice physics on simulations of climate change. Journal of Geophysical Research, 106, 19,639-19,655.

Lewis, J.P., Weaver, A.J., Johnston, S.T., Eby, M., 2003: The Neoproterozoic 'Snowball Earth': Dynamic sea ice over a quiescent ocean. Paleoceanography, 18, 4, doi:10.1029/2002PA000786, 1092.

Lewis, J.P., Eby, M., Weaver, A.J., Johnston, S.T., Jacob, R.L., 2004: Global glaciation in the Neoproterozoic: reconciling previous modelling results. Geophysical Research Letters, 31, 8, doi:10.1029/2004GL019725, L08201.

Matthews, H.D., Weaver, A.J., Eby, M., Meissner, K.J., 2003: Radiative forcing of climate by historical land cover change. Geophysical Research Letters, 30, 2, 27:1–27:4, doi:10.1029/2002GL016098, 1055.

Matthews, H.D., Weaver, A.J, Meissner, K.J., 2004: Terrestrial and carbon cycle dynamics under recent and future climate change. Journal of Climate. In press.

Matthews, H.D., Weaver, A.J., Meissner, K.J., Gillett, N.P., Eby, M., 2004: Natural and anthropogenic climate change: Incorporating historical land cover change, vegetation dynamics and the global carbon cycle. Climate Dynamics, 22, 461–479.

Meissner, K.J., Schmittner, A., Weaver, A.J., Adkins, J.F., 2003: The ventilation of the North Atlantic Ocean during the Last Glacial Maximum — A comparison between simulated and observed radiocarbon ages. Paleoceanography, 18(2), 1:1–1:13, doi:10.1029/2002PA000762, 1023.

Meissner, K.J., Weaver, A.J., Matthews, H.D., Cox, P.M., 2003: The role of land-surface dynamics in glacial inception: A study with the UVic Earth System Model. Climate Dynamics, 21, 515–537.

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

Saenko, O.A., Weaver, A.J., Gregory, J.M., 2003. On the link between the two modes of the ocean thermohaline circulation and the formation of global-scale water masses. Journal of Climate, 16, 2797–2801.

Saenko. O.A., Schmittner, A., Weaver, A.J., 2004: The Atlantic-Pacific seesaw. Journal of Climate, 17, 2033-2038.

Schmittner, A., Yoshimori, M., Weaver, A.J., 2002: Instability of glacial climate in a model of the ocean-atmosphere-cryosphere system. Science, 295, 1489-1493.

Schmittner, A., Meissner, K.J., Eby, M., Weaver, A.J., 2002: Forcing of the deep ocean circulation in simulations of the Last Glacial Maximum. Paleoceanography, 17, 2, 5:1–5:15, doi:10.1029/2001PA000633, 1015.

Schmittner, A., Saenko, O.A., Weaver, A.J., 2003: Coupling of the hemispheres in observations and simulations of glacial climate change. Quaternary Science Reviews, 22, 659–671.

Stouffer, R.J., Weaver, A.J., Eby, M., 2004: A method for obtaining pre-twentieth century initial conditions for use in climate change studies. Climate Dynamics, 23, 327–339.

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

Weaver, A.J., Eby, M., Wiebe, E.C., Bitz, C.M., Duffy, P.B., Ewen, T.L., Fanning, A.F., Holland, M.M., MacFadyen, A., Matthews, H.D., Meissner, K.J., Saenko, O.A., Schmittner, A., Wang, H., Yoshimori, M., 2001: The UVic Earth System Climate Model: Model description, climatology and application to past, present and future climates. Atmosphere-Ocean, 39, 361-428.

Weaver, A.J., Saenko, O.A., Clark, P.U., Mitrovica, J.X., 2003: Meltwater pulse 1A from Antarctica as a trigger of the Bølling-Allerød warm interval. Science, 299, 1709–1713.

Weaver, A.J., Hillaire-Marcel, C., 2004: Ice growth in the greenhouse: A seductive paradox but unrealistic scenario. Geoscience Canada, 31, 77–85.

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

Yoshimori, M., Weaver, A.J., Marshall, S.J., Clarke, G.K.C., 2001: Glacial termination: Sensitivity to orbital and CO_2 forcing in a coupled climate system model. Climate Dynamics, 17, 571-588.

Yoshimori, M., Reader, M.C., Weaver, A.J., MacFarlane, N.A., 2002: On the causes of glacial inception at 116KaBP. Climate Dynamics, 18, 383-402.