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Article

The Planet Simulator: Towards a user friendly model

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Abstract

The Planet Simulator is a Model of Intermediate Complexity (MIC) which can be used to run climate and paleo-climate simulations for time scales up to 10 thousand years or more in an acceptable real time. The priorities in development are set to speed, easy handling and portability. Its modular structure allows a problem dependent configuration. Adaptions exist for the atmospheres of Mars and of Saturn's moon Titan. Common coupling interfaces enable the addition of ocean models, ice models, vegetation and more. An interactive mode with a Model Starter (MoSt) and a Graphical User Interface (GUI) can be used to select a model configuration from the available hierarchy, set its parameters and inspect atmospheric fields while changing model parameters on the fly. This is especially useful for teaching, debugging and tuning of parameterizations. This paper gives an overview of the model's features. The complete model including sources and documentation is available at (www.mi.uni-hamburg.de/plasim).

Zusammenfassung

Der Planet Simulator ist als "Model of Intermediate Complexity" (MIC) in der Lage, Paläoklima- und andere Simulationen für 10.000 oder mehr Jahre in kurzer Realzeit durchzuführen. Die Prioritäten der Entwicklung liegen in der Geschwindigkeit, der einfachen Handhabung und der Portabilität. Sein modularer Aufbau erlaubt die Konfiguration problemangepasst zu modifizieren. Neben der Erdsystem-Modellierung wurden auch Adaptionen für die Atmosphären des Mars und des Saturnmondes Titan durchgeführt. Kopplungsschnittstellen ermöglichen die Einbindung anderer Komponenten, wie Ozeanmodelle, Eismodelle und andere. Ein interaktiver Modus, Modell-Starter und grafische Benutzeroberfäche, erlaubt eine Auswahl des Modells aus einer Hierarchie, die Voreinstellung der Parameter, die Ansicht von Feldern sowie die Änderung von Modellparametern während der Simulation. Dies ist besonders nützlich in der Lehre, beim Austesten von Änderungen und der Optimierung von Parameterisierungen. Diese Veröffentlichung gibt einen kurzen Überblick des Modellaufbaus. Das komplette Modellpaket inklusive Quellcode und Dokumentation kann vom Internet unter (www.mi.uni-hamburg.de/plasim) heruntergeladen werden.

1 Introduction

For more than two decades, climate research centers have been developing comprehensive general circulation models (GCMs) of high complexity, mostly for their research interests. As the complexity of these models has been and still is growing considerably on their way to Earth system models, it is not surprising that, for both education and research, models simpler than those comprehensive models at the cutting edge of the development, are becoming more and more attractive: They run fast and can be used to simulate millennia and longer timespans in relatively short real time. They can use inexpensive hardware like workstations with no need to buy time on mainframes. They may be reconfigured for simulating environments that are far away from our present climate and even atmospheres of other planets or moons. The diagnostic of the simulation is easier with fewer interactions occurring in the model. Finally, the understanding of atmospheric or climate phenomena and the identification of key mechanisms is enhanced. This class of models has been called EMIC (Earth System Models of Intermediate Complexity) by a group of researchers (CLAUSSEN et al., 2002). In comparison with EMICs (e.g. PUMA, CLIMBER) the atmosphere of the Planet Simulator is more comprehensive.

Following this intermediate complexity approach, the Planet Simulator introduced here differs from comprehensive models. Its key features are:

- **modular** – problem dependent configuration
- **parallel** – parallel computer and networks
- **scalable** – horizontal and vertical resolution
- **portable** – hardware independent code
- **interactive** – graphical user interface
- **structured** – clearly arranged and commented
- **transparent** – freely available source code
- **compatible** – supports MPI, GRIB, NetCDF

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Dynamical core and physical processes comprise a general circulation model (GCM) of planetary atmospheres. Stand-alone, the dynamical core is a simplified general circulation model like the Portable University Model of the Atmosphere, PUMA (FRAEDRICH et al., 2005b), which requires linear processes to run, like Newtonian cooling and Rayleigh friction, which parameterize diabatic heating and planetary boundary layer friction. Though simple, PUMA has been enjoying a wide spectrum of applications and initiating collaborations in fundamental research, atmospheric dynamics and education alike. Specific applications beyond those described by FRAEDRICH et al. (2003) are tests and consequences of the maximum entropy production principle (KLEIDON et al., 2003), synchronisation (LUNKEIT, 2001), spatio-temporal coherence resonance (PÉREZ-MUÑUZURI et al., 2005), and large scale dynamics of the atmospheres on Mars and Titan (SEGSCHNEIDER et al., 2005; GRIEGER et al., 2004).

Applying a model like the Planet Simulator in a university environment has various aspects: First, the code must be open and freely available as the software required to run it; it must be user friendly, inexpensive and equipped with a graphical user interface. Second, it should be a flexible and universal tool to be used by researchers designing their own experiments. Third, it should be suitable for teaching project studies in classes or lab, where students practice general circulation modeling, in contrast to technicians running a comprehensive GCM.

Building the Planet Simulator includes, besides an atmospheric GCM of medium complexity, other compartments of the climate system, for example, an ocean with sea ice, a land surface with biosphere, etc. Here these other compartments are reduced to systems of low complexity. That is, not unlike PUMA as a dynamical core with linear physics, the Planet Simulator consists of a GCM with, for example, a simple ocean/sea-ice module formulated in terms of a mixed layer/sea ice energy balance. The soil/biosphere module is introduced analogously. Thus, working the Planet Simulator is like testing the performance of an atmospheric or oceanic GCM interacting with various highly reduced subsystems in terms of their energy (and mass) balances.

Coding the Planet Simulator requires that it is portable to many platforms ranging from personal computers over workstations to mainframes; massive parallel computers and clusters of networked machines are also supported. The system is scalable with regard to vertical and horizontal resolutions, provides experiment dependent model configurations, and it has a transparent and rich documented code.

In the following we present the Planet Simulator: The model including the dynamical core, parameterizations and subsystems (Section 2), and the graphical user interface with user friendly model starter and on the fly display and interaction (Section 3). We conclude with a brief summary and outlook (Section 4).

2 Model

GCMs consist of a dynamical core based on the first principles, parameterizations for unresolved processes and representations of climate subsystems. In the following these modules are briefly presented for the Planet Simulator. A more comprehensive description may be found at (www.mi.uni-hamburg.de/plasim)

2.1 Dynamical core

The dynamical core of the Planet Simulator is based on the moist primitive equations representing the conservation of momentum, mass and energy. Adopted from PUMA, the dimensionless set of equations consists of the

- prognostic equations for the vertical component of the vorticity and the horizontal divergence
- first law of thermodynamics
- equation of state (with hydrostatic approximation)
- continuity equation
- prognostic equation for water vapour (specific humidity)

The equations are solved numerically on a terrain following σ-coordinate system (where σ is the pressure normalized by the surface pressure). In the horizontal direction, the conventional spectral approach with the spectral transform method is applied (ORSZAG, 1970; ELIASSEN et al., 1970). Finite differences are used in the vertical with the vertical velocity being defined between the 'full' (temperature, moisture, vorticity and divergence) levels. The equations are integrated in time with a leap-frog semi-implicit time stepping scheme (HOSKINS and SIMMONS, 1975; SIMMONS et al., 1978) with Robert/Asselin time filter (ROBERT, 1981; ASSELIN, 1972).

2.2 Parameterizations and subsystems

The effect of unresolved processes is included by simplified parameterizations for boundary layer fluxes and diffusion, radiation and moist processes with interactive clouds. The interaction with other climate subsystems is enabled by adding reduced models for land-surface processes, vegetation, ocean and sea ice.

Boundary layer and diffusion

The bulk aerodynamic formulas are used to parameterize surface fluxes of zonal and meridional momentum (wind stress), and sensible and latent heat. The calculation of the drag and the transfer coefficient follows ROECKNER et al. (1992) for the ECHAM-3 model based on LOUIS (1979) and LOUIS et al. (1982). A Richardson number dependence is given by Monin-Obukhov similarity theory.

Vertical diffusion representing the non-resolved turbulent exchange is applied to the horizontal wind components, the potential temperature and the specific humidity. The exchange coefficients are calculated by the mixing length approach as an extension of the similarity theory used to define the drag and transfer coefficients (ROECKNER et al., 1992).

The horizontal diffusion parameterization is based on LAURSEN and ELIASEN (1989), as in the ECHAM-3 model (ROECKNER et al., 1992). The diffusion is computed in spectral space.

Radiation

The short wave radiation scheme is based on LACIS and HANSEN (1974) for the cloud free atmosphere with Rayleigh scattering, ozone absorption and water vapor absorption. For the cloudy part, albedos and transmissivities for high-, middle- and low-level clouds may be either prescribed or parameterized (STEPHENS, 1984).

Long wave radiation for the clear sky uses a broad band emissivity method (SASAMORI, 1968). Clouds can be either treated as gray bodies with a prescribed cloud flux emissivity (grayness) or the cloud flux emissivity is obtained from the cloud liquid water content (STEPHENS, 1978; STEPHENS et al., 1984).

Ozone concentration used in the radiation scheme is prescribed. Either a three dimensional ozone distribution can be externally provided or an idealized annual cycle of ozone concentration can be used (GREEN, 1964).

Moist processes, clouds and dry convection

Local negative values of specific humidity are an artifact of spectral models. In the model, a simple procedure corrects these negative values by conserving the global amount of water.

The cumulus convection is parameterized by a Kuo-type convection scheme (KUO, 1965, 1974) with some modifications to the original Kuo-scheme. Large scale condensation occurs if the air is supersaturated. Condensed water falls out instantaneously as precipitation. No storage of water in clouds is considered. An iterative procedure is used to compute the values starting from the supersaturated state.

Cloud cover and cloud liquid water content are diagnostic quantities. The fractional cloud cover of a grid box is parameterized according to SLINGO and SLINGO (1991) using the relative humidity for the stratiform cloud amount and the convective precipitation rate for the convective cloud amount.

Possible phase changes of convective or large scale precipitation within the atmosphere or the condensational growth of cloud droplets are not considered in the model. However, a distinction between rain and snow fall at the surface is made. If the temperature of the lowermost level exceeds the freezing point, convective and large scale precipitation is assumed to be rain, otherwise all precipitation falls out as snow.

Dry convective adjustment is performed for layers which are dry adiabatically unstable. The adjustment is done so that the total sensible heat of the respective column is conserved. Wherever dry convection occurs, it is assumed that the moisture is completely mixed by the convective process as well.

Land surface and soil

The parameterizations for the land surface and the soil include calculation of temperatures for the surface and the soil, a soil hydrology and a river transport scheme. In addition, surface properties like the albedo, the roughness length or the evaporation efficiency are provided. As, at the moment, coupling to an extra glacier module is not available, glaciers are treated like other land points, but with surface and soil properties appropriate for ice. Optionally, a simple biome model can be used which uses a continuous, macroscopic description of vegetation properties (not based on plant functional types).

The surface temperature is computed from the linearized energy balance of the uppermost 0.2 meters of the ground. Below this top layer the soil column is discretized into 5 layers of thickness (0.4 m, 0.8 m, 1.6 m, 3.2 m, 6.4 m). The temperatures at the respective levels are computed by energy balance consideration.

The parameterization of soil hydrology comprises the budgets for snow amount and the soil water amount (bucket model). The local runoff is transported to the ocean by a river transport scheme with linear advection (SAUSEN et al., 1994). For each grid box (land and ocean costal points) the river water amount is computed.

Some additional quantities characterizing the land surface of each grid box need to be specified for use in the model: The land-sea mask and the orography, the global distribution of the surface roughness length, a background albedo, a glacier mask for permanent ice sheets, the bucket size for the soil water. For snow covered areas, the background albedo is modified to the actual albedo used in the radiation scheme.

Ocean and sea ice

Sea surface temperatures and sea ice distributions can either be prescribed by climatology or simulated by a

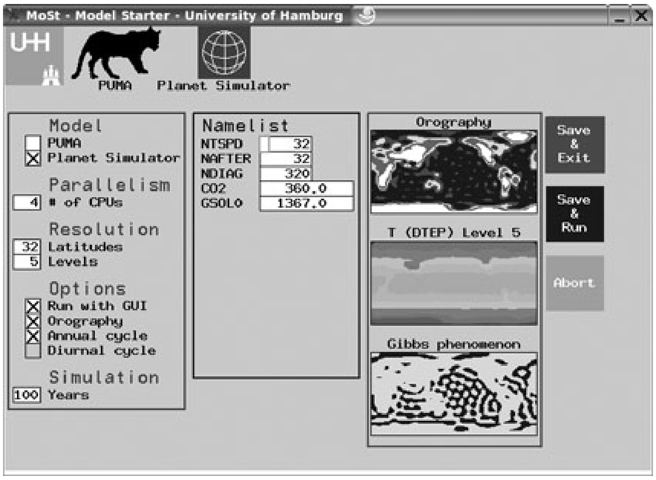

Figure 1: Screenshot of the Model Starter (MoSt).

mixed layer model with constant thickness and a thermodynamic sea ice model. Coupling to dynamical ocean models is under way and will be reported later.

3 Graphical user interface

The Planet Simulator may be used in the traditional fashion, with shell scripts, batch jobs, and network queuing systems. This is acceptable for long running simulations on complex machines and number-crunchers, like vector-computers, massive-parallel-computers and workstation clusters. There is now, however, a much more convenient method by using a graphical user interface (GUI) for model setup with parameter configurations and for interaction between user and model.

The Planet Simulator is configured and setup by the first GUI module named MoSt (Model Starter, screenshot in Figure 1). MoSt is the fastest way to get the model running. It gives access to the most important parameters of the model preset to the most frequently used values. The model can be started with a mouse click on the button labelled 'Save & Run' either with the standard parameter setting or after editing model parameters in the MoSt window. Some parameters, like horizontal and vertical resolution, or the number of processors, require the building (compile, link and load) of new executables. MoSt achieves this by generating and executing build scripts that perform the necessary code changes and create the required executable. Other parameters define startup- and boundary conditions or settings for parameterizations. In addition a graphical editor for orography, ground temperature and other boundary fields enables an easy setup of model experiments. All parameters can be edited in MoSt and, after a check for correct range and consistency, they are written to the model's namelist file.

Depending on all settings MoSt generates a runscript for the simulation. The user has the choice of leaving MoSt and continuing with the simulation under control of a GUI right away, or exiting MoSt with the scripts prepared to run. The second alternative is useful for users, who want to modify the setup beyond the scope of MoSt or want to run the Planet Simulator without GUI.

The GUI for running the Planet Simulator (screenshot in Figure 2) has two main purposes. The first one is to display model arrays in suitable representations. Current implementations are:

– Zonal mean cross sections

– Horizontal fields in cylinder/polar projection

– Time-longitude (Hovmoeller) diagrams

– Time series

– Numerical values

The second purpose is the interaction part of the GUI, which allows the user to change selected model variables during the model run. It is not necessary, though possible, to pause the model while changing variables. Changes to model variables are, of course, monitored in the output file and checked by GUI for the appropriate range of values and maximum possible change per timestep because a rapid parameter change or a choice of values beyond the normal range may blow up the model.

All model variables which are candidates for the display or interactive changes, have a special code to communicate with the Planet Simulator. The experienced modeller can add new code for more variables using the existing communication code as template. Thus all model fields or even fields received via coupling with other models can be put on the GUI display.

Both MoSt and GUI are implemented using the Xlib (X11R5), which is a library of routines for graphics and event communication. As this library is part of every UNIX/Linux operating system and base of all desktop environments, there is no need to install additional software for running MoSt and GUI. Another important property of Xlib is the full network transparency. The display of MoSt and GUI is not locked to the machine running the programs or the model. In fact, the best performance is obtained in running the Planet Simulator on two or four CPUs of a remote server while displaying the GUI on the user's workstation. In summary, the MoSt and GUI programs automate many tedious tasks, minimize the time to become familiar with the Planet Simulator, and make debugging and parameter tuning much easier. More kinds of presentations, coordinate projections and interactivity are being developed. A graphical preprocessor with editor for boundary conditions and a graphical postprocessor are future expansions to build an almost complete environment for modellers.

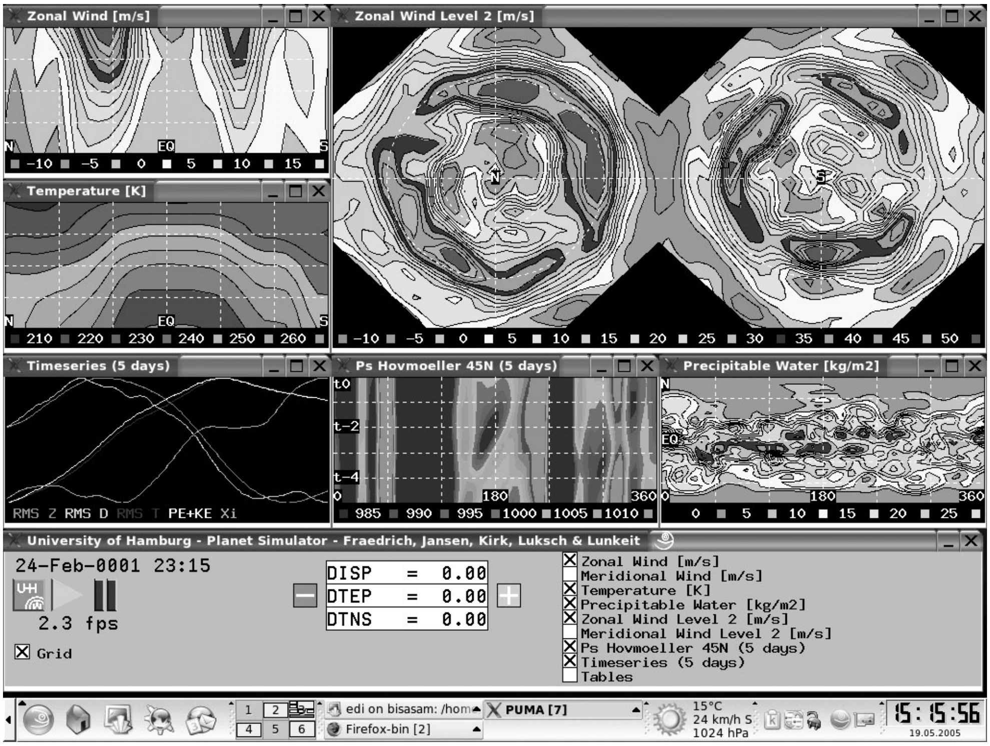

Figure 2: Screenshot of the Graphical User Interface (GUI).

4 Summary and outlook

The Planet Simulator introduced here is built to support numerical experiments for understanding the dynamics of the climate of the Earth and Earth-like planets and moons of the solar system. In this sense the Planet Simulator can be used as a simplified virtual laboratory to study the fundamental dynamical and thermo-dynamical issues, to identify feedbacks responsible for the long-term stability of the climate, and explore the causes of sudden losses of stability or abrupt change, like the impact of vulcanic eruption, the consequences of a thermohaline circulation breakdown, etc. Novel features of the Planet Simulator are: (i) a graphical user interface comprising a Model-Starter (MoSt) and user-computer interactive device (GUI), (ii) its embedding into a hierarchy of complexity with close model-relatives: the Portable University Model of the Atmosphere (PUMA as a simple GCM) and the Shallow Atmosphere Model (SAM), which share the same philosophy and, of course, coding principles, (iii) its embedding into a hierarchy of Earth-relatives: the Mars Planet Simulator and Titan Simulator (based on PUMA) are also available, (iv) the portable, scalable, modular open source code to instigate capacity building; that is collaboration in research, cooperation in teaching (e-learning), and progress in community model building.

Thus the Planet Simulator (and its relatives) should be considered as an open system in transit based on a dynamical core of the primitive equation atmosphere in the traditional spectral form and sigma coordinates. Given the set of modules, a basic platform for the Planet Simulator is achieved but, more modules are certainly needed to complete it, including, for example, continental ice sheets, more realistic land and marine biospheres, ocean models, geo-chemical cycles, etc. To test sensitivities or to create super ensemble forecasts, different modules of the same processes may also be useful. As for PUMA, fundamental research in atmospheric physics and dynamics, non-linear analysis and stochastic dynamics may be performed, now allowing for a more complete model hierarchy approach.

In subsequent papers we present applications of the Planet Simulator. A first application, comparing a green planet with a desert world, follows in this volume (FRAEDRICH et al., 2005a)

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