

# Earth-System Models of Intermediate Complexity

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## Background

Investigating the dynamic behavior of the Earth system remains a “grand challenge” for the scientific community. It is motivated by our limited knowledge about the consequences of large-scale perturbations of the Earth system by human activities, such as fossil-fuel combustion or the fragmentation of terrestrial vegetation cover. Will the system behave resilient with respect to such disturbances, or could it be driven towards qualitatively new modes of planetary operation?

This question cannot be answered, however, without prior analysis of how the unperturbed Earth system behaves and evolves in the absence of human influence. Such an analysis should, for example, provide answers to questions concerning the amplification of Milankovich forcing to glaciation episodes or the mechanisms behind the Dansgaard-Oeschger oscillations. But also more general questions may be addressed: Does life on Earth subsist due to an accidental and fragile balance between the abiotic world (the geosphere) and a biosphere that has emerged by chance? Or are there self-stabilizing feedback mechanisms at work as proposed by the GAIA theory? And, if the latter theory is valid, what is the role of humanity in GAIA’s universe?

## Towards a Definition of the Earth System and Earth System Models

Within IGBP - at least - the following definition of the “Earth system”, which has been proposed by Schellnhuber (1998, 1999) and Claussen (1998), for example, seems to be generally accepted: The Earth system encompasses the natural environment, i.e. the climate system according to the definition by Peixoto and Oort (1992), or sometimes referred to as the ecosphere, and the anthroposphere. The climate system consists of the abiotic world, the geosphere, and the living world, the biosphere. Geosphere and biosphere are further divided into components such as the atmosphere, hydrosphere, etc., which interact via fluxes of momentum, energy, water, carbon, and other substances. The anthroposphere can also be divided into subcomponents such as socio-economy, values and attitudes, etc.

So far, only simplified, more conceptual Earth system models exist. While models of the natural Earth system can be built upon the thermodynamic approach, this does not seem to be feasible for many components of the anthroposphere, in particular the psycho-social component. Hence development of a model of the full Earth system has to be undertaken in cooperation between IGBP and IHDP. For the time being, it will be the task of IGBP to pursue models of the natural Earth system in which anthropogenic activities are considered as exogenous forces and fluxes. Hence in the following, we consider only the natural Earth system.

Earth system models need to be globally comprehensive models, because the fluxes within the system are global (e.g. the hydrological cycle): changes in one region may well be caused by changes in a distant region. A currently open question is how much spatial (regional) resolution is required to appropriately capture processes with global significance. Earth system models probably need not capture all aspects of interaction between the spheres at the regional scale - although it will be interesting to test whether certain regional processes nevertheless affect global feedbacks.

## Models of Intermediate Complexity

During the past decades marked progress has been achieved in modelling the separate elements of the geosphere and the biosphere, focusing on atmospheric and ocean circulation, and on land

vegetation and ice-sheet dynamics. These developments have stimulated first attempts to put all separate pieces together, first in form of comprehensive coupled models of atmospheric and oceanic circulation, and eventually as so-called climate system models which include also biological and geochemical processes. One major limitation in the application of such comprehensive Earth system models arises from their high computational cost.

On the other hand, simplified, more or less conceptual models of the climate system are used for a variety of applications, in particular paleoclimate studies as well as climate change and climate impact projections. These models are spatially highly aggregated, for example, they represent atmosphere and ocean as two boxes, and they describe only a very limited number of processes and variables. The applicability of this class of model is limited not by computational cost, but by the lack of many important processes and feedbacks operating in the real world. Moreover, the sensitivity of these models to external forcing is often prescribed rather than computed independently (e.g. Houghton et al., 1997).

To bridge the gap, Earth System Models of Intermediate Complexity (EMIC's) have been proposed which can be characterize in the following way. EMIC's describe most of the processes implicit in comprehensive models, albeit in a more reduced, i.e. a more parameterized form. They explicitly simulate the interactions among several components of the climate system including biogeochemical cycles. On the other hand, EMIC's are simple enough to allow for long-term climate simulations over several 10.000 years or even glacial cycles. Similar to those of comprehensive models, but in contrast to conceptual models, the degrees of freedom of an EMIC exceed the number of adjustable parameters by several orders of magnitude. Tentatively, we may define an EMIC in terms of a three-dimensional vector: Integration, i.e. number of components of the Earth system explicitly described in the model, number of processes explicitly described, and detail of description of processes (See Figure 1).

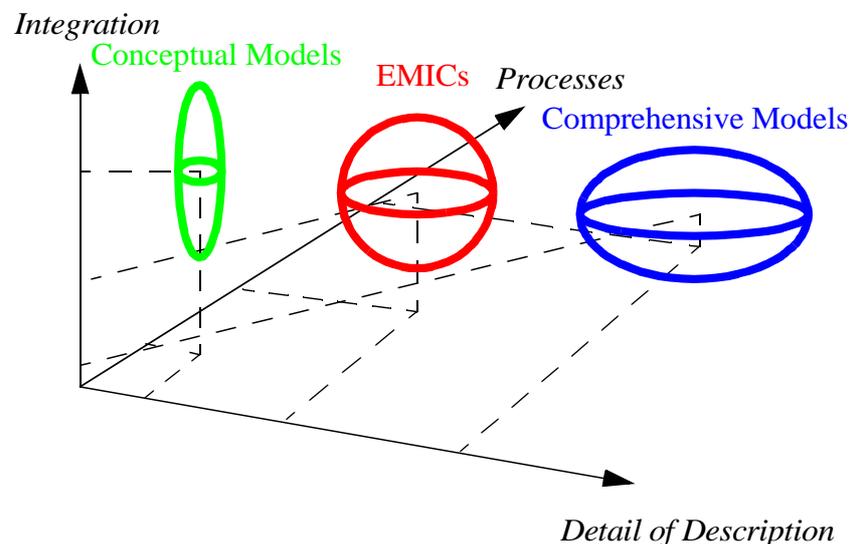


Figure 1: Tentative definition of EMIC's

Currently, there are several EMIC's in operation such as 2-dimensional, zonally averaged models (e.g. Gallée et al., 1991), 2.5-dimensional models with a simple energy balance (e.g. Marchal et al., 1998; Stocker et al., 1992), or with a statistical-dynamical atmospheric module (e.g. Petoukhov et al., 1999), and reduced-form comprehensive models (e.g. Opsteegh et al., 1998). EMIC's have been used for a number of palaeostudies, because they provide the unique opportunity of transient, long-term ensemble simulations (e.g. Claussen et al., 1999) - in contrast to

so-called time slice simulations in which the climate system is implicitly assumed to be in equilibrium with external forcings - which rarely is a realistic assumption. Also the climate systems behaviour under various scenarios of greenhouse gas emissions has been investigated exploring the potential of abrupt changes in the system (e.g. Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999). To illustrate the complexity of EMIC's we present - see Figure 2 - the structure of CLIMBER 2.3, an EMIC developed in Potsdam by Petoukhov et al. (1999).

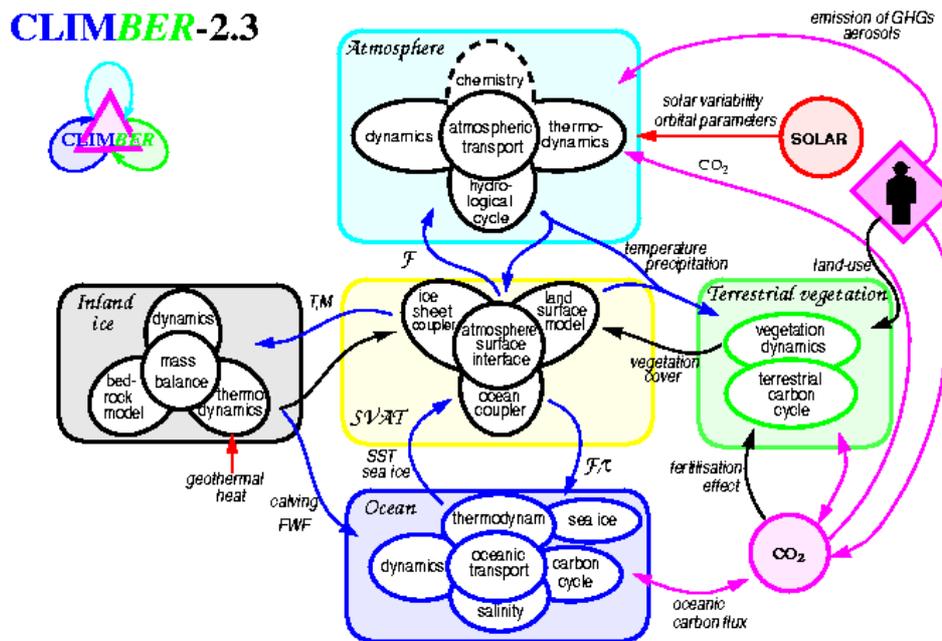


Figure 2: Structure of an EMIC

### Perspective

Earth System analysis generally relies on a hierarchy of simulation models. Depending on the nature of questions asked and the pertinent time scales, there are, on the one extreme, zero-dimensional tutorial or conceptual models like those in the “Daisyworld” family. At the other extreme, three-dimensional comprehensive models, e.g. coupling atmospheric and oceanic circulation with explicit geography and high spatio-temporal resolution, are under development in several groups.

During the IGBP Congress in Shonan Village, Japan, May 1999, and the IGBP workshop on EMIC's in Potsdam, Germany, June 1999, it became more widely recognized that models of intermediate complexity could be very valuable in exploring the interactions between all components of the natural Earth system, and that the results could be a more realistic than those from conceptual models. These meetings have pointed at the potential that EMIC's even might have for the policy guidance process, such as the IPCC.

Finally, it should be emphasized that EMIC's are considered to be one part of the above mentioned hierarchy of simulation models. EMIC's are not likely to replace comprehensive nor conceptual models, but they offer a unique possibility to investigate interactions and feedbacks at the large scale while largely maintaining the geographic integrity of the Earth system.

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