about the next decade of planetary research. As a matter of fact, the systems approach was adopted as the guiding research principle, and a strategic partnership with the international sister programmes was envisaged in order to create a joint venture that may be called "Integrated Earth Science". All the crucial points of this historical resolution are succinctly summarized in Berrien's abovementioned contribution.

For GAIM, this is an extremely encouraging development that puts the Waikiki Principles on a solid basis and into the right context. As a minor consequence, the renaming of GAIM into "Global Analysis, *Integration* and Modelling" has been approved meanwhile. Much more important, however, is the induced mandate for GAIM to explore from now on all intrinsic and extrinsic options for systems-analytic progress, both from the topical and the methodological point of view. An exciting opportunity to demonstrate pertinent skills will be provided by the new initiative on "Surprises and Nonlinearities in Global Change", recently launched by GCTE. This is actually an issue of paramount importance for Earth System science as will be emphasized, i.a., by the Third Assessment Report of the IPCC. The New GAIM has already started to think about establishing an international postdoc network for advancing research on the "irregular side of Global Change".

Let me conclude with two caveats. First, we should not be carried away now by a frenzy of integrationist enthusiasm. I firmly believe that the so-called reductionist approach to Earth Science will still have to constitute the backbone of our research body in the decades to come: Yes, the whole is more than the sum of its parts, but the sum of zeros is zero. Second, systems science is by no means an easy exercise. We will need to employ the most advanced methodologies available like the ones that have been developed by the complex dynamics community. It is high time for joining forces with this cognitive community and similar ones, yet this will become a rather challenging enterprise.

Compared with the opportunities ahead, my caveats carry little weight though. We are lucky to live in this era of Global Scientific Change.

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Earth System Models of Intermediate Complexity

by Martin Claussen, Andrey Ganopolski, John Schellnhuber and Wolfgang Cramer

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 combus-tion or the fragmentation of terrestrial vegetation cover. Will the system be 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 psychosocial 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

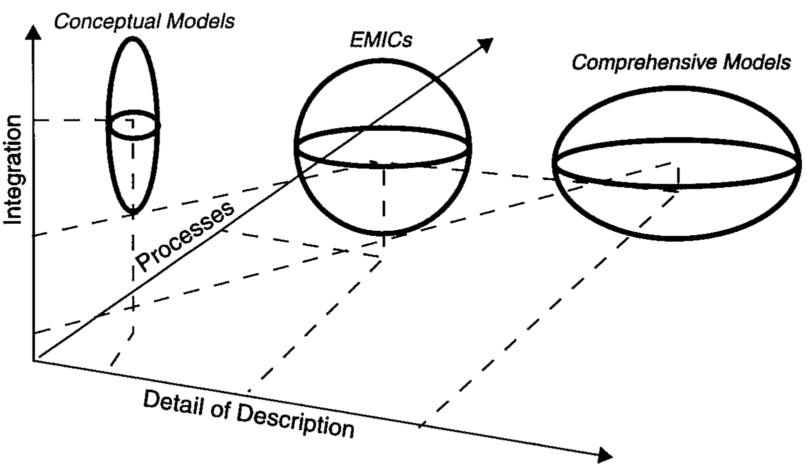

Figure 1. Tentative definition of EMIC's

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

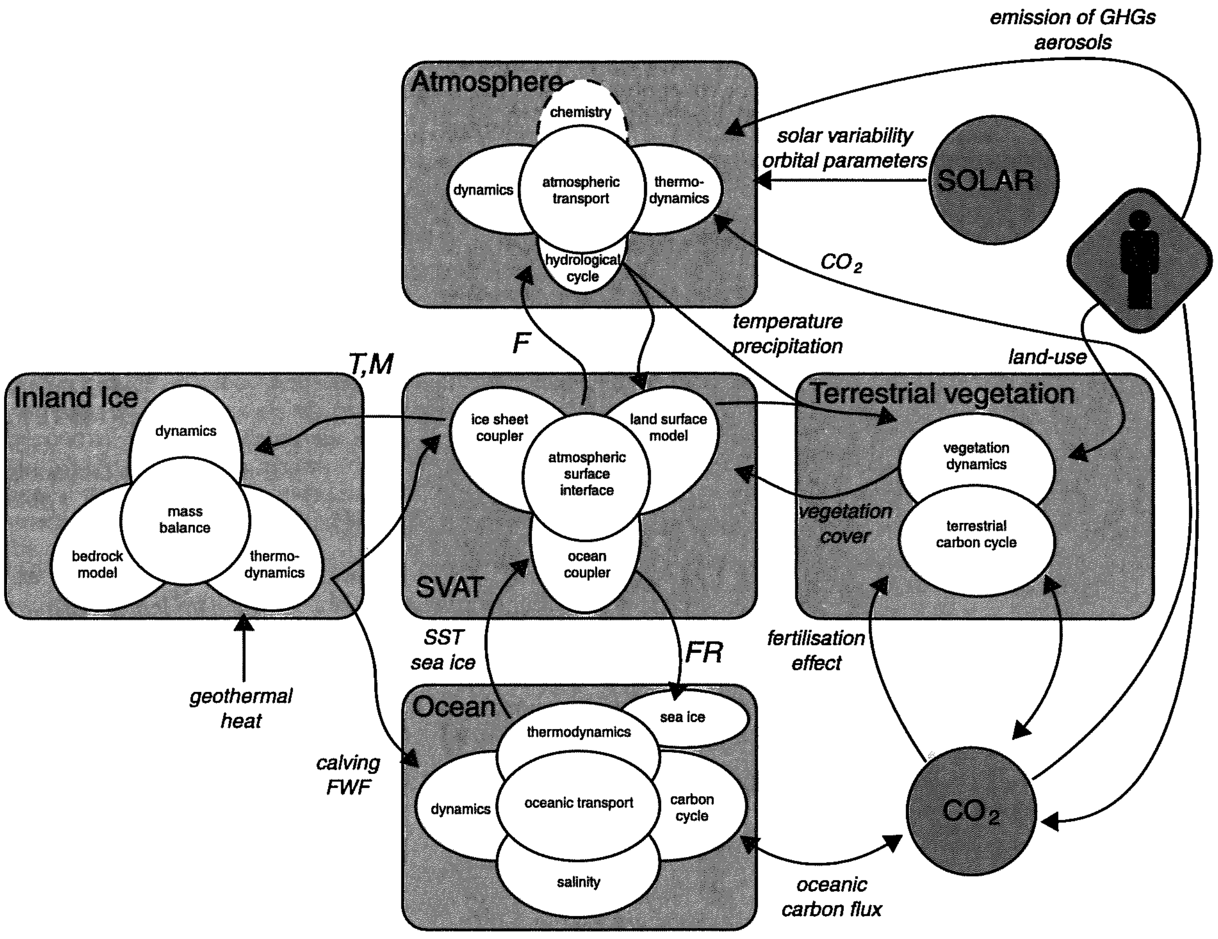

Figure 2. Structure of an EMIC

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 (EMICs) have been proposed which can be characterized in the following way. EMICs 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, EMICs 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).

Currently, there are several EMICs 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).

EMICs have been used for a number of palaeostudies, because they provide the unique opportunity for 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 system's 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 EMICs we present - see Figure 2 - the structure of CLIMBER 2.3, an EMIC developed in Potsdam by Petoukhov et al. (1999).

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 EMICs 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 more realistic than those from conceptual models. These meetings have pointed at the potential that EMICs might have even for the policy guidance process, such as the IPCC.

Finally, it should be emphasized that EMICs are considered to be one part of the above mentioned hierarchy of simulation models. EMICs 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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