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# Sustaining Earth's life support systems – the challenge for the next decade and beyond

by Berrien Moore III, Chair, IGBP

Integration, interdiscplinarity, and a systems approach mark the emerging ethos in IGBP as the Programme evolves rapidly into its second decade of international global change research.

In late February in Cuernavaca, Mexico, the Scientific Committee of the IGBP held a landmark meeting in which it was decided that the strength and maturity of the Programme would allow an increased emphasis on the systemic challenges of Global Environmental Change. The strength has been made particularly apparent in the developing Core Project syntheses.

This strength and capability of the IGBP at this point in time is extraordinarily valuable since the SC-IGBP also recognised that the challenges of Global Environmental Change demand a treatment of the full Earth System. It is simply a reality that a scientific understanding of the Earth System *is required* to help human societies develop in ways that sustain the global life support system.

The core of the IGBP Programme for the next decade will be built around three interlocking and complementary structures:

- Core projects that focus on key processes will continue to be the foundation for the IGBP;
- A formal integrated study of the Earth System as a whole, in its full functional and geographical complexity over time, and
- A focus on three cross-cutting issues where advances in our scientific understanding are required to help human societies develop in ways that sustain the global life support system.

The research will be undertaken in the context of an expanding and strengthening collaboration with the International Human Dimensions Programme on Global Environmental Change (IHDP) and the World Climate Research Programme (WCRP). The new challenge is to build, on our collective scientific foundation, an international programme of Earth System Science. This effort will be driven by a common mission and common questions, employing visionary and creative scientific approaches, and based on an ever-closer collaboration across disciplines, research themes, programmes, nations, and regions.

Driving the new structures and approaches are two critical messages that have become ever clearer through the past decade plus of global change research.

First, the Earth functions as a system, with properties and behaviour that are characteristic of the system as a whole. These include critical thresholds, 'switch' or 'control' points, strong nonlinearities, teleconnections, and unresolvable uncertainties. Understanding components of the Earth System is critically important, but is insufficient on its own to understand the functioning of the Earth System as a whole.

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Second, humans are a significant force in the Earth System, altering key process rates and absorbing the impacts of global environmental changes. In fact, the environmental significance of human activities is now so profound that the current geological era can be called the 'Anthropocene' epoch (see article by Paul Crutzen and Eugene Stoermer in this issue of the NewsLetter).

Global biogeochemical cycling will remain at the core of IGBP research, but the Programme will evolve towards a more systematic structure with major activities located in the three compartments – atmosphere, oceans, and land – and in the three interfaces between them. These six domains will more formally guide the emerging Core Projects for the next decade. This theme is already apparent within the IGBP. For instance, LOICZ is positioned well at the Land-Ocean interface, and the emerging Surface Ocean Lower Atmosphere Study (SOLAS) is clearly headed in this direction. We are asking, in this formulation, hard and challenging questions. How can we join better JGOFS science with GLOBEC science? How can we bridge more strongly and with less duplication the scientific agendas of BAHC and the Global Energy Water Experiment (GEWEX) within the WCRP? Similarly, how do we better link in the future IGAC with SPARC (Stratospheric Processes and their Role in Climate)? What should be the nature of the future GCTE, and how does it tie more closely with LUCC?

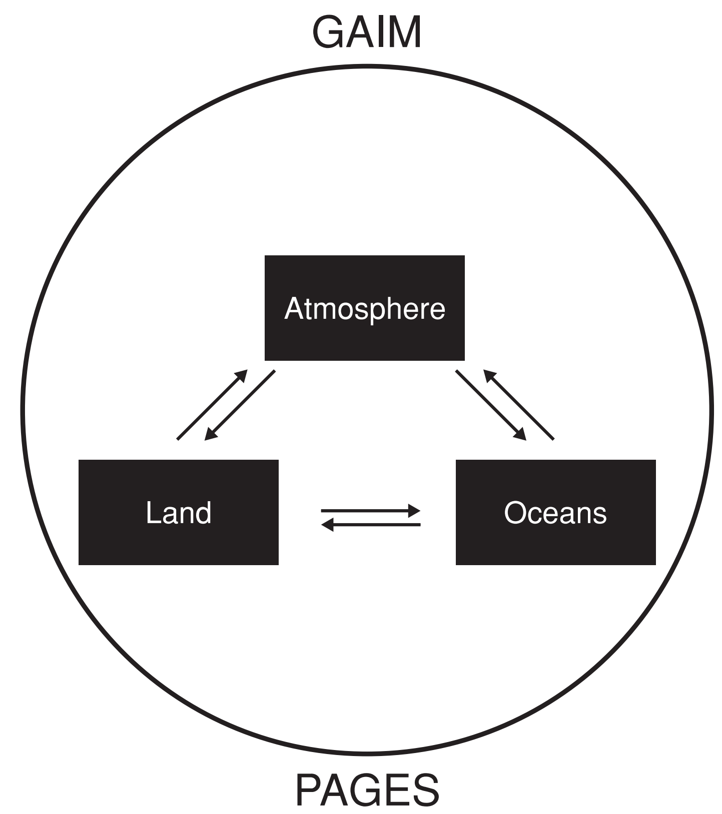

Figure 1.

GAIM is being reoriented towards integrating across this structure to focus on the Earth System as a whole (see John Schellnhuber's article in this issue of the NewsLetter). PAGES work provides an essential longer time context for the dynamics of the Earth System as well as for parts of it. The accompanying figure shows the new structure.

It is hoped that at least three new joint projects will be launched with WCRP and IHDP on crosscutting issues of major societal relevance. Three linked issues are currently in the planning stages – the Global Carbon Cycle, Water Resources, and an initiative on Global Change and Food and Fibre, with an emphasis on food vulnerability/security and opportunity analysis. Additional major issues, such as human health and ecosystem goods and services, are under consideration.

These joint projects, which are clearly crosscutting in nature, will depend critically upon the research in the Core Projects of the IGBP, IHDP and WCRP that is already being undertaken or is planned. Considerable co-ordination is needed, however, to bring these elements into a more integrated framework, and some new work will need to be initiated where gaps are identified. Strategic partnerships are being developed with other research institutions outside the three programmes and with policy and management institutions to ensure that the work is designed and implemented in ways that facilitate its application.

The Global Carbon Cycle joint project is the most advanced, with a series of activities planned for the rest of 2000. A small scoping meeting in April developed much of the human dimensions contributions to the effort, while additional meetings in May (Lisbon, Portugal) and October (Durham, New Hampshire, USA) will complete the definition of a common international framework to help guide research at national, regional and global scales, and will design a series of focused activities for 2001 and beyond.

For the Food and Fibre joint project, a scoping meeting with IHDP and WCRP was held in Paris in early March, which began to defined the overall structure for the research. Further planning meetings are proposed for June/July (Reading, UK), October (London), November/December (Stockholm) and February 2001 (Washington) to complete the preparation of a science plan and implementation strategy.

The initial co-ordination meeting for the Water Resources joint project is tentatively scheduled for September.

These initiatives will place great demands on the IGBP. The strength of the Programme will be tested and new structures will be demanded. The recently expanded role of the IGBP-DIS with its important work in both regional and global studies will add essential new capabilities, including support for our key regional studies (see the article on The Regional Data Bundle Concept by Wolfgang Cramer in this NewsLetter).

This continuing evolution of the IGBP in concert with the WCRP and the IHDP is important and merits the thoughts of all. We continue to welcome and need insights on directions, processes, objectives, and goals and the processes by which they may be realised. These pages are genuinely open to your contributions. The challenges of global environmental change are not going to vanish.

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# The Waikiki Principles: rules for a new GAIM

by John Schellnhuber Chair, GAIM

The first NewsLetter in the new millennium provides a convenient canvas for re-sketching the basic mission of GAIM, that is, pioneering Earth System science into a state of novel quality. This sounds rather preposterous yet turns into a solid ambition upon closer inspection of (i) the giant explorative strides taken by the big global research programmes (IGBP, WCRP, IHDP, etc.) during the last years, and (ii) the opportunities arising from the think-tank character of GAIM. Let me briefly elaborate on both aspects in the following.

In a recent essay for the Millennium Supplement of Nature (Vol. 402, Supp. 2 Dec 1999, C19-C23) I argued that the "Second Copernican Revolution" is just around the corner. This revolution reverses, in a way, the glorious first one by looking back on our planet from a (real or virtual) distance, striving to understand the so-perceived system as a whole and to develop concepts for global environmental management. The scientific trans-discipline thus emerging may be called *Earth Systems analysis*; it is supposed to yield a unified formalism for describing the make-up and functioning of the ecosphere machinery as well as its susceptibility to erratic or judicious human interventions. Ultimately, Earth System analysis will even be able to address the challenge of sustainable development in a no-nonsense way by deducing the macro-options for future ecosphere-antroposphere co-evolution from first cognitive and ethical principles.

In order to achieve all this, we clearly still have a long way to go, but the signs of hope accumulate at an ever increasing pace. Take, for instance, the growing stream of insights arising from the separate Core Projects of IGBP as highlighted at the Second IGBP Congress held in Japan last May (see Berrien Moore's keynote in Global Change Newsletter 38, and Will Steffen's reflections in Research GAIM, Summer 1999). This breathtaking progress was most impressively illustrated by Hugh Ducklow's lecture on the unravelling of the mysteries of the global oceanic flux system. So it seems that "all" that remains to be done is to take the scientific bits and pieces and to put them together.

But integration is much more than a synthetic book-keeping exercise – remember that it took evolution almost 4 billion years to compose the human brain from macro-molecules available already in the early days of life. The virtual scientific reconstruction of the planetary machinery ("Gaia") is not much smaller a task, although we expect it to be accomplished in less than a couple of eons. What will be needed, at any rate, is a sophisticated *integration methodology* as transpiring, e.g., from the modern theory of complex non-linear dynamic systems, and it will be necessary to account for all sorts of deterministic and stochastic uncertainties.

This is the point where the New GAIM enters the scene: During the recent meeting of the Task Force in Waikiki, Hawaii (31 January – 2 February 2000), the integration challenge was intensively discussed and identified as *the* central research issue of the next decade of global change science. And the group, which embraced the top representatives and executives of IGBP, concluded unanimously that GAIM shall become the central driving force for Earth System analysis by fully utilizing the potential resulting from its cross-sectoral design. In order to be specific, an explicit survey among the participants was conducted for revealing individual priorities and suggestions regarding the longer-term targets to be met. A clear-cut picture emerged which may be summarized in the following three "*Waikiki Principles*".

I. GAIM is to explore and promote cognitive opportunities arising from the appropriate combination of Core Project results and tools. This means, in particular, to play the role of a trans-project topics scout and a feasibility assessor.

II. GAIM is to advance the integration of wisdom inside and outside IGBP. This means, on the one hand, to make available the best integrative methodologies and, on the other hand, to include the systems and problems dimensions primarily investigated by the sister programmes WCRP and IHDP.

III. GAIM is to implement Earth System analysis by organizing the construction, evaluation and maintenance of a hierarchy of Earth System models. This means, in particular, to help generate models of different degrees of complexity and to employ the resulting complementary ensemble for conducting virtual planetary experiments with respect to past, present, and future global changes.

As a consequence, the acronym GAIM should from now on stand for "Global Analysis, Integration and Modelling". Principle I is illustrated by the TRACES (Trace Gas and Aerosol Cycles in the Earth System) Initiative; principle II by the intra-IGBP Carbon Project and the envisaged inter-programmatic cross-cutting themes like water and food and fibre; principle III by the EMIC (Earth System Models of Intermediate Complexity) Initiative and the "Flying Leap" towards a fully coupled state-of-the-art ocean-atmosphere-biosphere model. There is no doubt that GAIM will keep on providing the IGBP community with sophisticated services like well-designed model and data intercomparisons, but its thrust will be focussed on research at the Earth-system level.

It has to be emphasized that the Waikiki Rules for the New GAIM have yet to be approved by the "legislative and executive bodies" of IGBP, but I am confident that they will gladly help to open up this avenue towards the scientific horizon.

Here end my pre-Cuernavaca contemplations on the New GAIM. In the meantime, the Scientific Committeee of IGBP held a meeting which undoubtedly deserves the qualification as a "landmark event" (see Berrien Moore's article in this issue of the NewsLetter). I have to confess that I did not expect the SC to make so far-reaching and far-sighted decisions 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 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

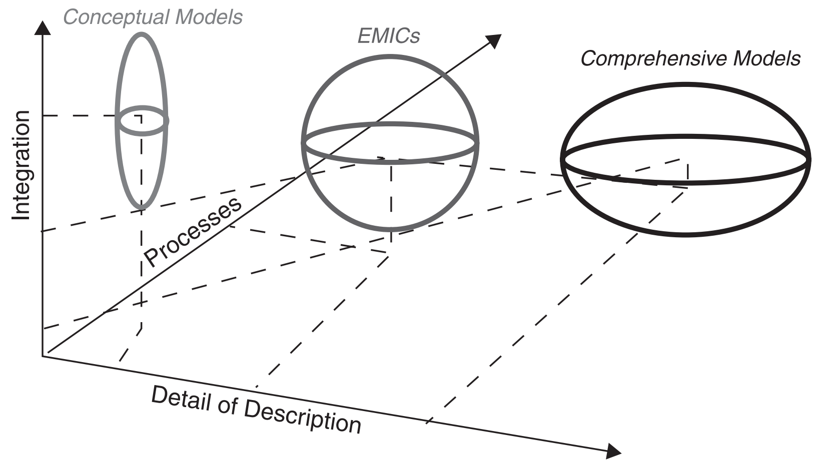


Figure 1. Tentative definition of EMIC's

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

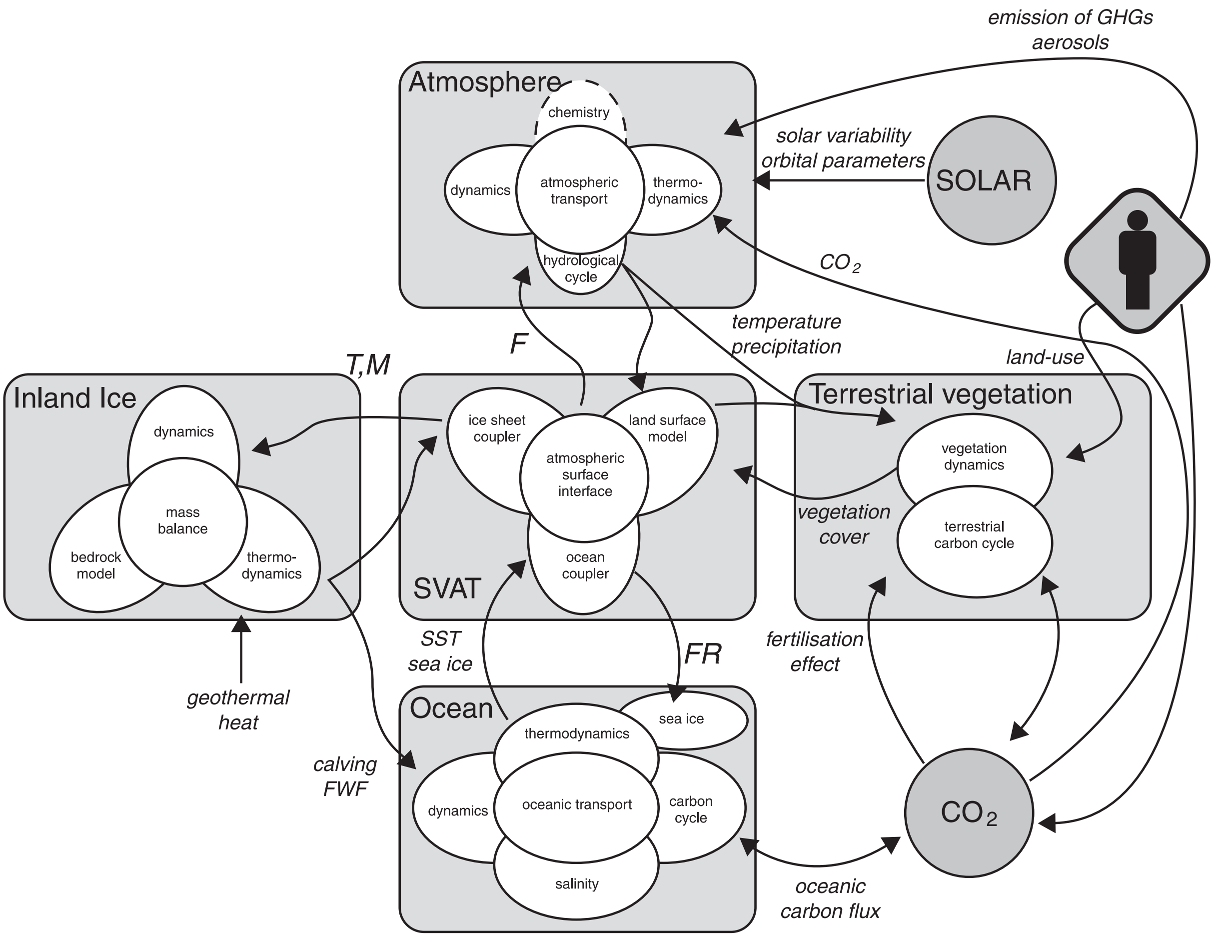


Figure 2. Structure of an EMIC

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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# Full-Form Earth System Models: Coupled Carbon-Climate Interaction Experiment (the "Flying Leap")

by Inez Fung, Peter Rayner, and Pierre Friedlingstein; Edited by Dork Sahagian

Investigating the dynamic behaviour and complexities 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. 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 preliminary 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 also include biological and geochemical processes. It has been the rule rather than the exception that surprising behaviour has emerged when these components are coupled.

Major challenges lie at the boundaries between subsystems with regard to efforts to couple models and develop integrated Earth System models. The development of a coupled model involves relaxation of prescribed boundary conditions so that modelled subsystems can interact directly. As such models are run over time, one measure of their success is the stability with which they characterize the Earth System without the need for "flux corrections" to adjust for model drift in an *ad hoc* manner.

In general, Earth System analysis 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 intermediate level, "Earth-system Models of Intermediate Complexity" (EMICs) can run for long model times, and capture most of the critical interactions between system components, but do not include all processes within each part of the Earth System. At the other extreme are three-dimensional full-form comprehensive models, e.g. coupling atmospheric and oceanic circulation with explicit geography and high spatio-temporal resolution, can be used to explore the detailed interactions and feedbacks between processes that operate primarily within subsystems such as the terrestrial ecosystem, atmosphere, ocean, etc.

Each of these types of models can be useful and full-form models are considered to be one part of a hierarchy of simulation models. Information passes in both directions through this hierarchy. An effect noted first in an EMIC should normally be sought in a full-form model. Also, the candidate processes for a phenomenon noticed in a full-form model should be included in an EMIC to test our understanding.

It would be unrealistic at present to expect to be able to develop full-form models that can be used as working simulations of the Earth System. However, for short time slices and under certain conditions, such comprehensive models can be practical, and only such models can answer certain key questions about the Earth System and our understanding of the key processes that drive responses of the system to anthropogenic perturbations. One such question is "How robust must our understanding be of the internal processes of subsystems (e.g. terrestrial ecosystems, atmospheric circulation, marine productivity) before coupling subsystem models reduces uncertainty inherent in the coupled system rather than increasing it?"

At the October 1998 meeting of WCRP/WGCM (Working Group on Coupled Modelling) in Melbourne (chair: L. Bengtsson), a proposal from GAIM for a collaborative IGBP/GAIM – WCRP/WGCM project to investigate carbon-climate interactions was discussed and tentatively approved. The project would introduce terrestrial and oceanic carbon cycle modules into coupled atmosphere-ocean-land climate models, in essence to introduce $CO_2$ as a prognostic variable in the climate model, to investigate the co-evolution of climate and $CO_2$ given emission scenarios (rather than concentrations) of the greenhouse gas. The excitement lies in the identification and investigation of interactions in a climate space beyond known experience. The project is referred to as "The Flying Leap" to emphasize the uncertainties and excitement of the endeavour.

The "Flying Leap" experiment will focus on $CO_2$ emissions and concentration and the response of the Earth System to $CO_2$ forcing, given a fixed scenario for future emissions. This experiment uses an emissions scenario that would give an increase in atmospheric $CO_2$ concentration of 1%/yr without coupling or feed backs.

While this may be a modest increase relative to "business as usual" scenarios, it provides a useful baseline for this initial development and application of a full-complexity model.

The protocol for the experiment was discussed at the IGBP GAIM Task Force meeting in Honolulu, January 31-February 2, 2000. The goal of the experiment is to evaluate the sensitivity of the coupled carbon-climate system to anthropogenic perturbations. The procedure is to solve simultaneously the coupled family of equations for different specifications of external source/sinks of $CO_2$ and other greenhouse gases. See Figure 1.

$$\frac{f\ (CO_2)}{f\ (t)} = F_{ba} - F_{ab} + F_{oa} - F_{ao} + \textit{External Sourcres/Sinks} = f\ (climate)$$

$$\frac{f\ (climate)}{f\ (t)} = f\ (CO_2,\ \text{other GHGs})$$

Where $F_{ba}$ and $F_{ab}$ are the fluxes of carbon between the terrestrial biosphere and the atmosphere and $F_{oa}$ and $F_{ao}$ are the equivalent fluxes between the ocean and the atmosphere.

Figure 1. Coupled equations describing climate -$C0_2$ interaction.

The experiments will involve a control for the pre-industrial era with no external sources/sinks of $CO_2$, and a forward integration from the pre-industrial to beyond AD2000 for a specified emission scenario for $CO_2$ and the other greenhouse gases. No trace gas cycles will be included for the other greenhouse gases. Instead, they will be converted to $CO_2$-equivalents and added to the radiatively active $CO_2$ in the atmosphere. The $CO_2$-equivalents will not be interactive with the terrestrial and oceanic carbon dynamics.

To start, $CO_2$ release from fossil fuel combustion would be specified as a global value (PgC/yr) as a function of time based on a scenario that would have given a 1%/y increase in the absence of climate feedbacks on the carbon uptake. The terrestrial and oceanic modules would be geographically resolving, to take account of the differential ecosystem/circulation effects on the carbon exchange. The terrestrial and oceanic uptake would be summed over area to yield annual values (PgC/yr) of their uptakes.

Carbon uptake by the biosphere and oceans would respond to the instantaneously simulated climate. In this way, carbon-climate interactions are included to determine the rate of $CO_2$ increase and consequently the rate of climate warming.

The experimental protocol identifies the principal fully coupled carbon-climate calculations as well as several offline calculations that help to isolate the importance of the processes. If atmospheric composition feedbacks significantly modify rates of climate change in the simulations, the mechanistic understanding will suggest regions and processes to monitor in the real world.

The experiment is in three general phases.

1) Spin-up and stability. Here we equilibrate the various carbon cycle components forced with pre-industrial atmospheric concentrations and climate before coupling the subsystems. The coupled system should be stable but slow drift has characterized many other such coupled systems and must not be discounted.

2) Historical period. With prescribed emissions of $CO_2$ and other gases, we run the models from about 1800 until 2000. We can test the atmospheric concentration and distribution of $CO_2$ and its isotopes in such models against ice core and direct atmospheric data.

3) Beyond 2000. We use projected emissions with atmospheric composition feedbacks turned on or off to investigate their magnitude. Also we use climates produced by the feedback or no feedback cases to investigate the impact of such feedbacks on permissible emissions for stabilization. Off-line experiments will elucidate which processes contribute to the feedbacks. It is important to note here that the experiment will draw on previous experience so that, for example, the different climate sensitivities of the participating models can be accounted for.

In the contemporary carbon budget, the fossil fuel source is ~5% of the one-way gross terrestrial or oceanic flux. Small annual carbon flux imbalances or errors, like air-sea heat and freshwater flux errors, if sustained over a long-enough time, may lead to significant climatic migrations. Other likely surprises may come from nonlinearities in terrestrial and oceanic carbon dynamics or in the climate system. Hence the experiments should viewed as one exploration of the nonlinearities inherent in the Earth System.

One should treat the "Flying Leap" as a grand challenge to our understanding of the carbon cycle as well as of carbon-climate interactions. It should be the stimulus to take the models to another level. Glimpses of realism should be hoped for, but their absence should not be causes for despair. Much can be learned during the process of model development, intercomparison, and refinement.

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# An integrated approach to understanding Earth's metabolism

by Will Steffen

Ice core and other palaeo records provide a fascinating window on the metabolism of Earth over hundreds of thousands of years. No record is more intriguing than the rhythmic 'breathing' of the planet as revealed in the Vostok ice core records of temperature and $CO_2$ and $CH_4$ concentrations (Petit et al., 1999, and Figure 1).

The highly regular waxing and waning of Earth's climate and atmospheric composition through the glacial-interglacial cycles provided the thematic context for a recent meeting of the IGBP Carbon Working Group. The workshop was the first in a series of five workshops, co-sponsored by the IGBP, the Royal Swedish Academy of Sciences, Stockholm University, and the Swedish University of Agricultural Sciences, aimed at addressing focused topics in the IGBP synthesis project. The objective of the October 1999 meeting was to synthesis our current understanding of nutrient interactions with the carbon cycle in terrestrial, marine and coastal systems.

Although the workshop participants discussed and debated many aspects of carbon-nutrient interactions, the remarkably regular planetary metabolic pattern embodied in the Vostok ice core record held a particular fascination. It is a classic example of 'control theory'. It shows cyclic variations of relatively long cold (glacial) periods interrupted by shorter warm (interglacial) periods. The atmospheric $CO_2$ concentration varied from 180-200 ppmV during the glacial periods to 265-280 during the interglacials. The palaeo records show other interesting details in the pattern: (i) during the glacial terminations, the increase in atmospheric $CO_2$ is in phase with southern hemisphere warming; melting of the northern hemisphere ice caps lags by thousands of years; (ii) the strong coupling between temperature and atmospheric $CO_2$ suggests that the latter is probably the primary amplifier of climate change during glacial terminations; and (iii) the periodicity of the cycles shows a strong correspondence to the cyclic variations in the Earth's orbit, although the associated changes in incoming solar energy are not enough to drive the glacial-interglacial cycling on their own.

Many hypotheses have been put forward to explain the glacial-interglacial cycling, but most remain essentially disciplinary, usually based on one aspect of the Earth system such as ocean-atmosphere dynamics. The aim of the IGBP Carbon Working Group was not to develop yet another hypothesis or to provide 'the answer' to the glacial-interglacial puzzle, but rather to show that when the Earth system behaves in such a highly regular and reproducible fashion, a strongly integrated, interdisciplinary approach offers the best chance to advance our understanding.

The explanation developed at the October workshop goes something like this:

The precise nature of the upper and lower limits of atmospheric $CO_2$ concentration are evidence of strong control mechanisms – both terrestrial and oceanic biological processes are critical elements of the control loop. Biogeochemical interactions between land and ocean transfer control from one to the other on a periodic basis.

How do the control loops work? The lower level of ca. 180 ppmV for atmospheric $CO_2$ represents something of an 'ecosystem/biome compensation point'. Below that level systems lose almost as much carbon through respiration as they can take up through photosynthesis in the cold, dry $CO_2$-depleted climate. As we see below, this has implications for the transfer of nutrients between land and ocean. The upper limit (280 ppmV) is the point at which the solubility-driven flux of $CO_2$ from the ocean to the atmosphere is balanced by the uptake of $CO_2$ by the terrestrial and oceanic biota.

How is control passed between terrestrial and ocean systems? There is strong evidence that the glacial phase (terrestrial control) is terminated initially by an increase in solar radiation due to a change in the Earth's orbit (Milankovich

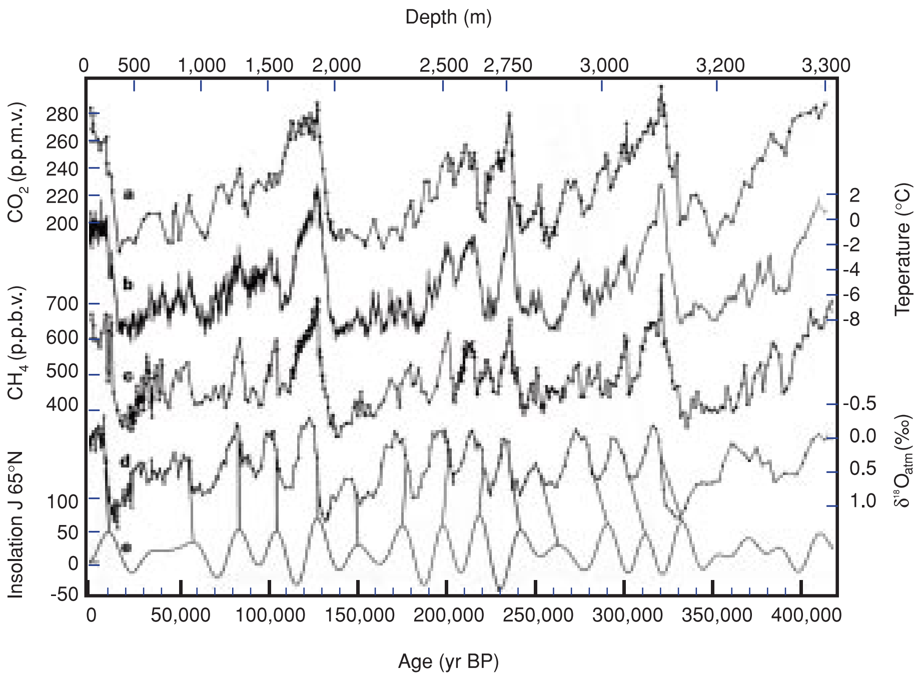


Figure 1. Glacial-interglacial dynamics of the Earth system as recorded in the Vostok ice core. Adated from Petit et al. 1999

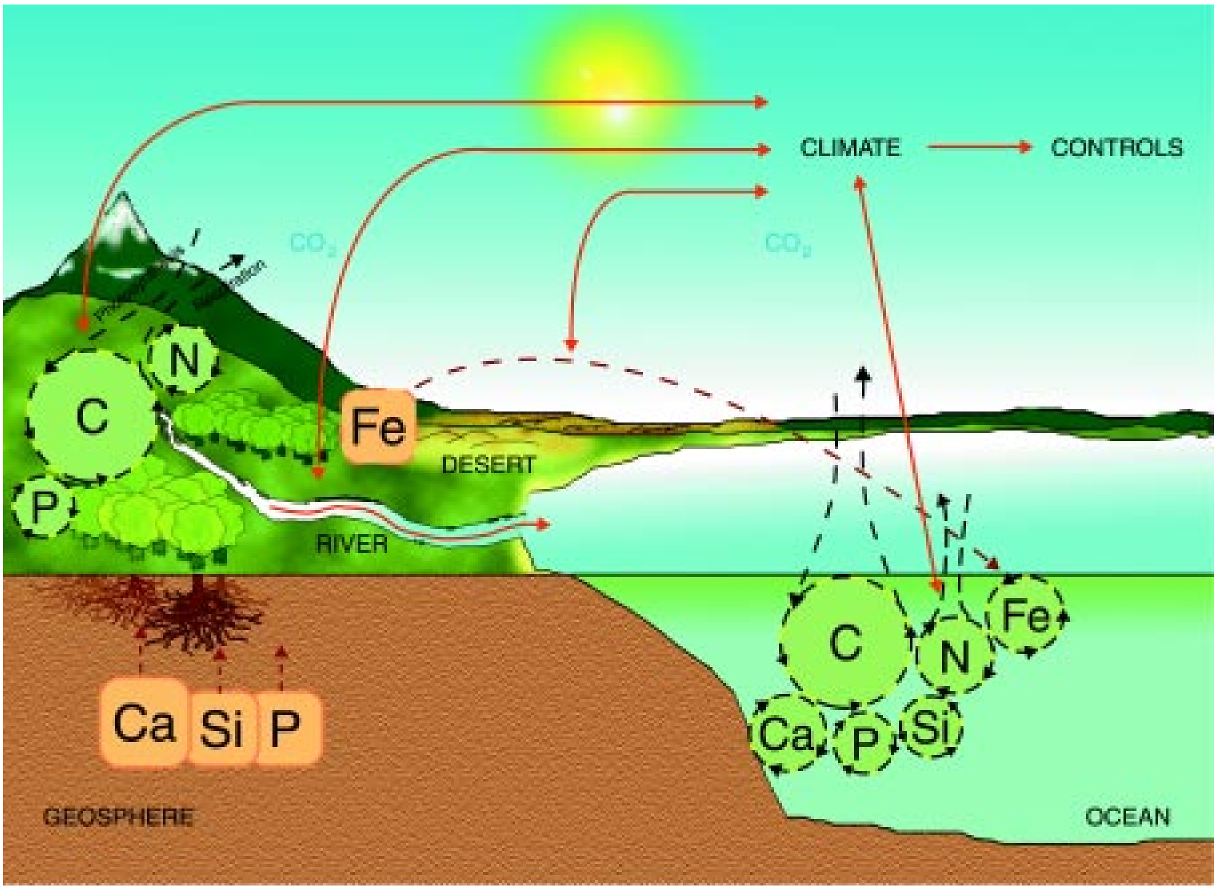


Figure 2. Cartoon illustrating glacial-interglacial hypothesis on linked ocean -land biogeochemical cycling.

forcing); this could trigger a reorganisation of oceanic circulation and stimulate the hydrological cycle. The initial warming would start to accumulate greenhouse gases such as $H_2O$, $CO_2$ and $CH_4$ in the atmosphere, due to, for example, the reduced solubility of $CO_2$ in warmer water. Also, melting icecaps in the northern hemisphere and the northwards expansion of forests would reduce the Earth's albedo, absorbing more incident solar radiation and further warming the planet, releasing even more oceanic $CO_2$ in a positive feedback loop.

But as the climate warms and $CO_2$ concentration increases, the increasing activity of the terrestrial biosphere accelerates the mobilisation of elements such as P, Si and Fe from the geosphere through enhanced root activity. These elements eventually leak from the terrestrial biosphere into rivers and to the coastal ocean. Over thousands of years these nutrients are entrained into the oceanic circulation and, in areas of upwelling, stimulate oceanic net primary production and increase the drawdown of $CO_2$ from the atmosphere. The increasing biotic uptake of $CO_2$ in both oceans and land eventually matches the solubility-driven outgassing of $CO_2$ and the system reaches a balance

at an atmospheric concentration of $CO_2$ of about 280 ppm.

But the invigorated activity of the terrestrial biosphere is already sowing the seeds of its own "destruction". The interglacial balance appears to be precarious, and the vigour of terrestrial and marine biological uptake overtakes the outgassing from the oceans. This triggers a set of feedbacks – initial cooling, increasing solubility of $CO_2$, increasing sea ice and further cooling – which drive the system towards the glaciated state. Although the terrestrial biosphere is taking up less $CO_2$, it also releases P that was tied up in

This article continues on page 16.

# Highlights of GAIM's first phase: building towards Earth System Science

by Dork Sahagian

The 'New GAIM', as described in John Schellnhuber's article in this issue, is oriented strongly towards an integrative systems approach to studying the global environment. This is not a completely novel task for GAIM, however; over the past decade much work has been done to lay a solid foundation on which to build an Earth System Science effort.

The goal of GAIM has been to advance the study of the coupled dynamics of the Earth System using as tools both data and models. The challenge to GAIM has been to initiate activities that will lead to the rapid development and application of a suite of Global Prognostic Biogeochemical Models. In GAIM's first several years, attention was focused on

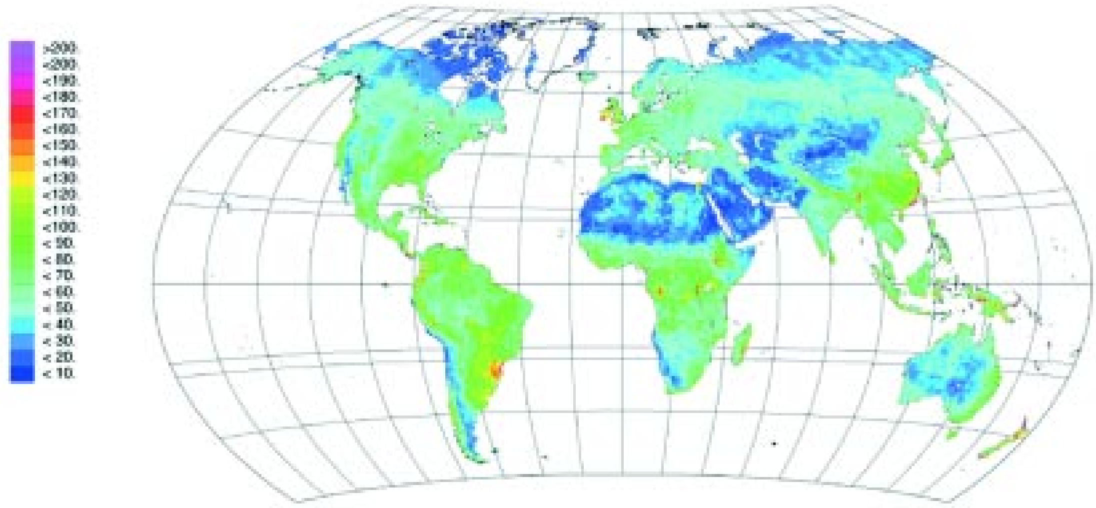


Figure 1a. Annual net primary production (g C $m^{-2}$ $yr^{-1}$) estimated as the average of all model NPP estimates.

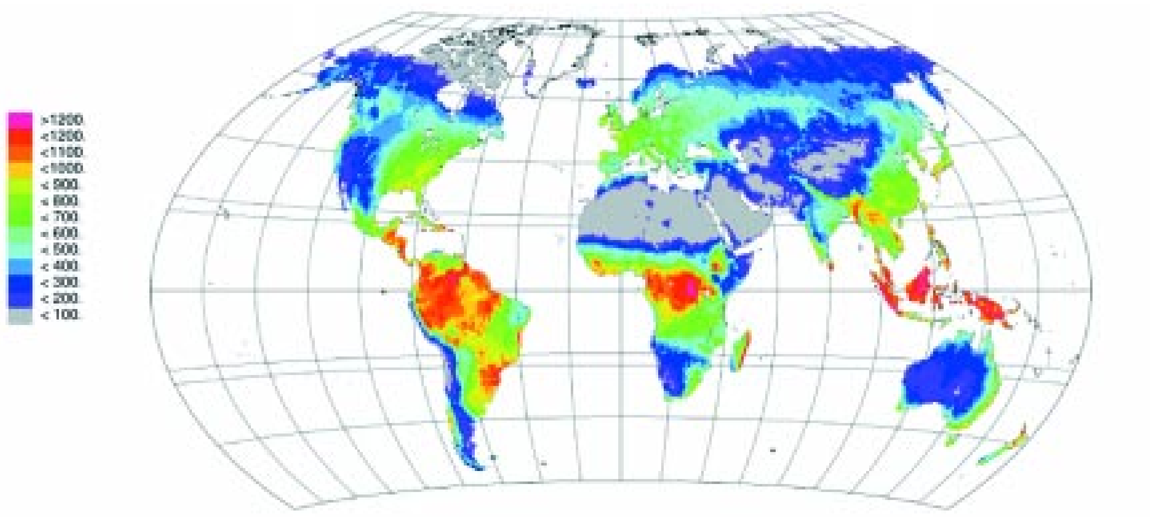


Figure 1b. Spatial distribution of the variability in NPP estimates among the models as represented by the standard deviation of model NPP estimated in a grid cell.

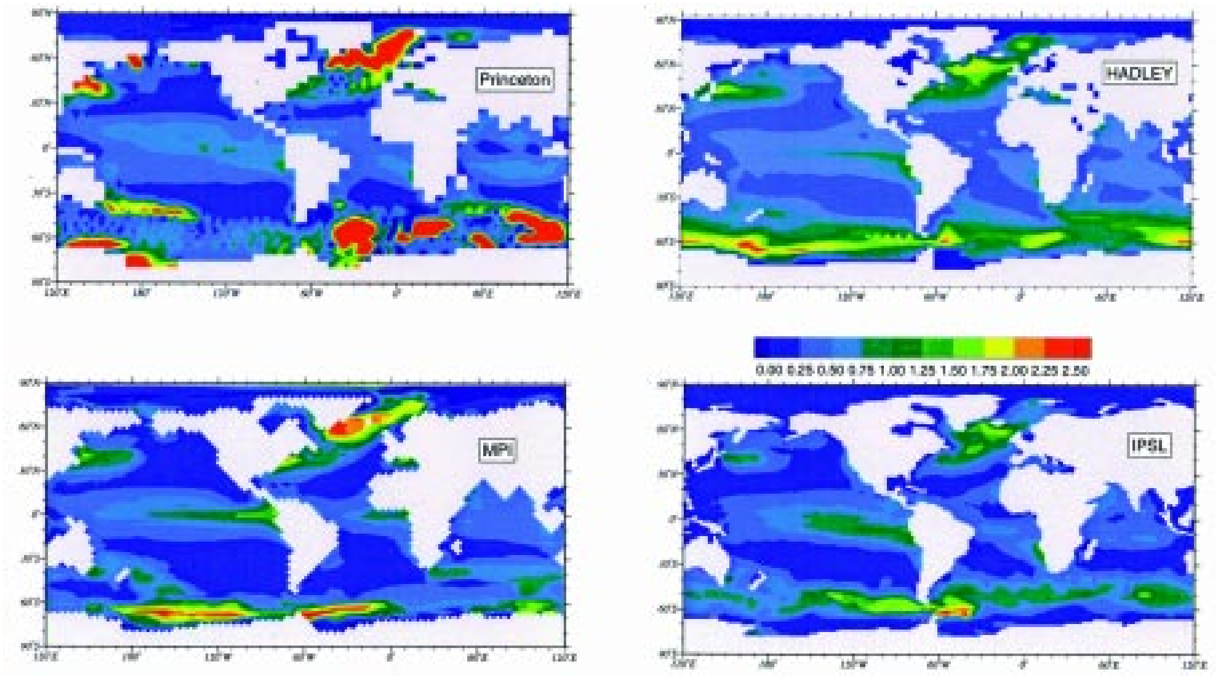


Figure 2. Annual mean air-sea flux of anthropogenic $CO_2$ in 1990.

developing the conceptual and procedural tools necessary to meet this challenge. This entailed scrutiny of each of the three main subsystems on the Earth, and the development and refinement of terrestrial, marine, and atmospheric carbon models in preparation for integrated Earth System model development. Much of the progress to date in modelling specific components within the global biogeochemical subsystems sets the context for modelling activities within the various IGBP Core Projects. The GAIM activity is by definition cross-cutting; therefore, the activities of GAIM intersect fundamentally with all the IGBP Core Projects.

During the last decade, there has been enormous progress in the development of biogeochemical models for significant components of the Earth System. Build-

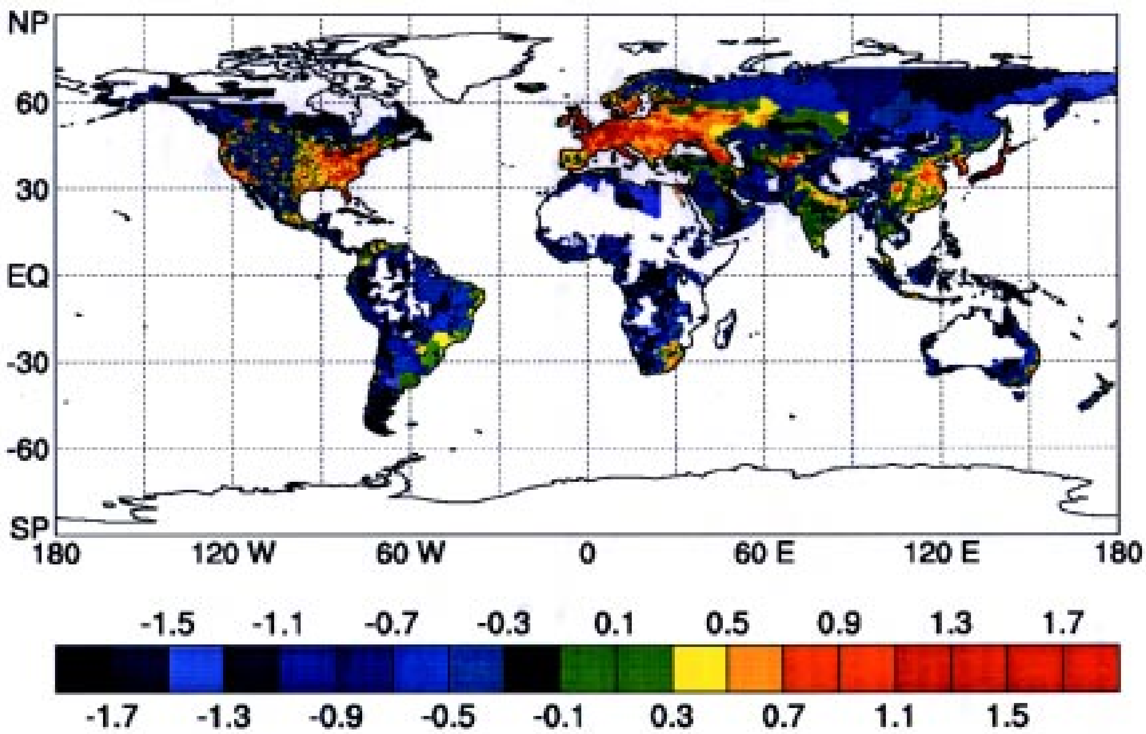


Figure 3. Model simulation of the distribution of $SF_6$ emissions for 1992.

ing upon process-based models for ecosystem metabolism in a variety of terrestrial systems, the scientific community began to extend these models to global scales. Ocean carbon cycle models were developed, compared and evaluated by incorporating carbon chemistry and crude biological concepts in ocean general circulation models; atmospheric tracer transport models were developed and evaluated on the basis of comparison of inversion results and observed atmospheric tracer concentrations and sources; and finally, the initial steps were taken to begin to link these component models with atmospheric GCMs. This has set the stage for a more comprehensive Earth System approach to global biogeochemical cycling and the development of prognostic models at various levels of complexity.

As part of its "Analysis" program, GAIM devoted considerable effort in identifying gaps in both conceptual understanding and data that would be necessary for modelling purposes. Working toward filling those gaps, GAIM has convened a number of targeted workshops on topics such as Wetland Biogeochemical Functioning (GAIM report #2), Regional Interactions between Climate and Ecosystems (GAIM Report #3), and Sea Level and Global Hydrology (GAIM Report #8). In addition, outreach programs such as the African GAIM Modelling Workshop (GAIM Report #1), targeted at entraining more of the developing world into international global change research, have added to our pool of expertise. All of these activities are aimed toward placing the research community in a stronger position to develop the global prognostic biogeochemical models that are the ultimate goal of GAIM.

Among the most significant results produced by GAIM to date is a set of techniques for comparing and assessing complex model performance. Without the ability to assess models developed by the global change research community, there will be no basis for making reliable projections regarding future system responses to anthropogenic forcing, and no way for the community to properly contribute to the IPCC process beyond broad scenario-based projections. Whereas individual scientists or modelling groups can and do develop numerical models of various aspects of the Earth System, the value of the results of isolated models is greatly enhanced by comparison with other models. The discrepancies in model results between different approaches to the same problem provide critical insights into model shortcomings, and pave the way for model refinement and improvement.

GAIM's techniques for assessing model performance emerged from a set of model intercomparison activities, beginning with the Net Primary Productivity (NPP) model intercomparison. Prior to the NPP Intercomparison project, several different terrestrial ecosystem models existed nationally and internationally, but their results were vastly different. This was alarming, given that they were describing the same system. Through the model intercomparison process developed by the GAIM Task Force, techniques were devised to both compare model results in an objective manner, and to determine the sources of model result differences. This process made it possible for individual model developers to return to their labs and refine or correct their models on the basis of what was learned at the intercomparison workshops. The same type of process was applied to ocean models in the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP), and to the atmosphere in the Atmospheric Tracer Transport Model Intercomparison Project (TransCom). GAIM's three major sub-system level model intercomparison projects are described below. Each of the three were highlighted as special sessions at the last IUGG meeting (July 23, 1999 Birmingham, UK). The tools devised through these activities will be applied to the interpretation and assessment of the broader Earth System models now being developed (e.g. EMIC, Flying Leap. See other articles in this NewsLetter).

## Global Net Primary Productivity: A model intercomparison

### Task Leaders: Wolfgang Cramer, Kathy Hibbard

Global primary production of ecosystems on land and in the oceans is a crucial component of biogeochemical model development within IGBP. As key components in the terrestrial carbon cycle, geographically referenced net primary productivity (NPP) and gross primary productivity (GPP) and their corresponding seasonal variation are needed to enhance understanding of both the function of living ecosystems and also their effects on the environment. Productivity is also a key variable for the sustainability of human use of the biosphere by, for example, agriculture and forestry. Recently, it has become possible to investigate the magnitude and geographical distribution of these processes on a global scale by a combination of ecosystem process modelling and monitoring by remote sensing. Since agricultural and forestry production provide the principal food and fuel resources for the world, monitoring and modelling of biospheric primary production are important to support global economic and political policy making.

For estimates of the global carbon balance, a large amount of uncertainty centers on the role of terrestrial ecosystems. Geographically referenced gross primary productivity (GPP), net primary productivity (NPP), and heterotrophic respiration ($R_h$) and their corresponding seasonal variation are key components in the terrestrial carbon cycle. At least two factors govern the level of terrestrial carbon storage. First and most obvious is the anthropogenic alteration of the Earth's surface, such as through the conversion of forest to agriculture, which can result in a net release of $CO_2$ to the atmosphere. Second, and more subtle, are the possible changes in net ecosystem production resulting from changes in atmospheric $CO_2$, other global biogeochemical cycles, and/or the physical climate system. The significant influence of the terrestrial biosphere on the global carbon balance and hence on the problem of climate change has become more widely recognized during the past two decades, and now the role of terrestrial ecosystems is recognized to be an important factor influencing the concentration of carbon dioxide in the atmosphere.

One of the early results that emerged from the first of a series of NPP model intercomparison workshops, "Potsdam '94", was that a major reason for differences between outputs of the same variable between different models was that the input data for the same variable were from different sources and carried different uncertainties (this was true for both ground-based observations such as climatic data and for remote sensing data such as AVHRR-derived NDVI). Consequently, many of these data were standardized for the second workshop, "Potsdam '95." The composite results of the models are illustrated in Fig 1a, in which the NPP values are averaged amongst the 17 participating models. While the results appear reasonable, it should be stressed that there were large differences between models (Figure. 1b).

The NPP model intercomparison has made it clear that existing data must be chosen and used in a standardized way if like models are to be compared, and ultimately, if complementary models are to coupled. It has also clarified data gaps which can now be filled before models can reliably simulate the role of terrestrial ecosystems in the global carbon cycle. However, it is not necessary for model development to wait until all gaps in the global observing systems are closed.

Rather, IGBP can take the lead in coordinating existing and future data sources in a way that will optimize their utility throughout the global change research community.

The NPP intercomparison activity revealed a strong need to not only compare models to each other, but to some objective measure of performance. This measure can only come from validation data that is difficult to obtain directly for NPP. However, indirect information is available that bears on NPP, and this was compiled in a "Gross Primary Productivity Data Initiative (GPPDI), which then led to the current effort to assess model performance using data from specific key sites from around the world in a new Ecosystem Model-Data Intercomparison (EMDI).

The objective of EMDI is to compare model estimates of terrestrial carbon fluxes (NPP and net ecosystem production (NEP), where available) to estimates from ground-based measurements, and improve our understanding of environmental controls of carbon allocation. The primary questions to be addressed by this activity are to test simulated controls and model formulation on the water, carbon, and nutrient budgets with the observed NPP data providing the constraint for autotrophic fluxes and the integrity of scaled biophysical driving variables. The experimental design consists of a multi-tiered approach to make maximum use of the available NPP and NEE measurements. These tiers include site model-data comparisons, grid-cell model-data comparisons, global model-data comparisons, and flux data. The NPP data sets emerging from GPPDI are derived from both point and spatially explicit sampling designs, thus enabling a valid comparison between point and area-based models and data. Analyses and visualizations are being carried out within each tier to investigate the model controls on NPP and their underlying formulations. Initial results showed general agreement between models and data but with obvious differences that indicate areas for potential data and model improvement.

## Ocean Carbon-Cycle Model Intecomparison Project (OCMIP)

### Task Leaders: Jim Orr, Patrick Monfray, Ray Najjar

The ocean plays a critical role in the global carbon budget because the solubility of $CO_2$ in seawater provides an enormous reservoir for sequestration (or release) of atmospheric $CO_2$. Thus, the goal of the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) is to identify the principal differences between global-scale, three-dimensional, ocean carbon-cycle models, to accelerate their development, and to improve their predictive capacity.

OCMIP's primary concern has been to focus on the abilities of models to predict ocean carbon distributions and air-sea fluxes of $CO_2$. The first phase of OCMIP is complete (GAIM Report #7, 1998), and OCMIP-2 is now underway (http://www.ipsl.jussieu.fr/OCMIP/). The OCMIP-1 strategy was to study (1) natural $CO_2$ fluxes, with simulations which were allowed to reach equilibrium with pre-industrial atmospheric $CO_2$ (at 278 ppm), and (2) anthropogenic $CO_2$ fluxes, with simulations forced by observed atmospheric $CO_2$ from pre-industrial time to present. In addition, to evaluate model behaviour, OCMIP-1 compared simulated vs. observed $^{14}C$ distribution. A global network of $^{14}C$ samples was taken during GEOSECS in the 1970s and more recent sections from WOCE are now available. Natural $^{14}C$ offers a powerful test of an ocean model's deep ocean circulation; "bomb $^{14}C$" helps constrain the modelled circulation of surface and intermediate waters. Bomb $^{14}C$ also appears to exhibit similar behaviour to anthropogenic $CO_2$ under certain conditions. Exploiting the $^{14}C$- $CO_2$ relationship, when appropriate, offers one way to circumvent the difficulty of directly measuring the small anthropogenic change in dissolved inorganic carbon (DIC) in the ocean, relative to the large DIC pool which is naturally present.

OCMIP Phase 1 demonstrated that predictions from ocean carbon-cycle models differ regionally by a substantial amount, particularly in the Southern Ocean, where modelled air-sea fluxes of anthropogenic $CO_2$ are also largest (Fig. 2). The recently launched OCMIP-2 involves 13 models and additional simulations. The focus remains on $CO_2$, but OCMIP-2 also includes emphasis on new circulation tracers, such as CFC-11 and CFC-12, and new biogeochemical tracers such as $O_2$. OCMIP-2 also includes simulations with a common biogeochemical model so that participants can better study effects due to differences in modelled ocean circulation. OCMIP-2 also includes data specialists who are leading the JGOFS and WOCE synthesis for $CO_2$, $^{14}C$, and CFCs, thus strengthening model validation efforts.

Standard simulations for CFC-11 and CFC-12 have been completed by all 13 participating OCMIP-2 model groups. The AJAX section for CFC-11 reveals large differences between storage of that tracer in the Southern Ocean, e.g., south of 50°S. Almost all other forward models struggle to get adequate CFC-11 vertical penetration in the south. Only the models with a coupled sea-ice model do a reasonable job. An interesting feature is the observed bump at around 40°S which is characteristic of formation of intermediate waters. Models with explicit mixing along surfaces of constant density (isopycnals) do a reasonable job of capturing this feature; other models with only horizontal and vertical mixing do a much poorer job.

Studies during the first two phases of OCMIP have relied on ocean models run under present climatological conditions, where circulation patterns do not evolve with time. Beyond OCMIP-2, future work will probably focus on the impact of changing climate on marine biogeochemistry as well as the feedback of changes in marine biogeochemistry on climate. To validate such simulations, it will be crucial to focus on how well models are able to reproduce observed interannual variability.

## Atmospheric Tracer Transport Model Intercomparison Project (TRANSCOM)

### Task Leader: Scott Denning

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) is part of a larger GAIM research program focused on the development of coupled ecosystem-atmosphere models that describe the time evolution of trace gases with changing climate and changes in anthropogenic forcing. Much of our current understanding about the global carbon cycle has come from observing the changes in atmospheric $CO_2$ concentrations over time. Time series (e.g., Mauna Loa record) provide insight into the seasonal cycle as well as global source/sink and interannual variations. Additionally, existing flask networks (e.g. CMDL, CSIRO, etc.) provide information about the distribution of atmospheric $CO_2$. For example, a disproportionate amount of fossil fuel emissions occur in the northern hemisphere, and a large terrestrial $CO_2$ sink is required to explain the weak observed north-south gradient. However, an accurate quantitative interpretation of the spatial structure requires realistic models of trace gas transport.

Chemical tracer transport models (CTMs) are used to study atmospheric $CO_2$ and can be characterized by the mechanisms they incorporate to transport tracers horizontally and vertically across the globe. One class of CTMs transport

$CO_2$ using offline analyzed winds from weather forecast centers or Global Circulation Models (GCMs), others actually calculate tracer concentrations with a GCM internal to the transport model. There are considerable model-dependent differences in simulating the global movement of atmospheric tracers.

The goal of TransCom is to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in the simulated transport. An important source of uncertainty in these calculations is the simulated transport itself, which varies among the many transport models used by the community. TransCom investigators have conducted a series of 3-dimensional tracer model intercomparison experiments which are intended to (1) quantify the degree of uncertainty in current carbon budget estimates that results from uncertainty in model transport; (2) identify the specific sources of uncertainties in the models; and (3) identify key areas to focus future transport model development and improvements in the global observing system that will reduce the uncertainty in carbon budget inversion calculations.

The first phase of TransCom compared model performance for two salient features of atmospheric $CO_2$: the annual mean north-south gradient (dominated by fossil fuel emissions), and the seasonal cycle (dominated by exchange with terrestrial ecosystems). Twelve modelling groups from four continents participated; many of the models have been used extensively in carbon cycle research. The experimental design for both the annual and seasonal simulations consisted of model runs for at least three years from an initial atmosphere with uniform $CO_2$, providing sufficient time for the model atmosphere to establish an "equilibrium" (annually repeating) concentration distributions. Each set of model results were normalized such that the January global three-dimensional mean was zero. Results showed a surprising degree of variance among models with regard to meridional north-south gradient at the surface, and especially aloft.

To understand the performance of the various models with respect to the inter-hemispheric gradients of passive tracers, TransCom needed to move beyond the simulations of unobserved (and unobservable) fossil fuel $CO_2$ to a tracer that is well observed and whose atmospheric budget is not complicated by missing sinks. This required a tracer with well-documented concentrations around the world, with a quantifiable emissions field, and preferably with insignificant sinks. For TransCom Phase II, sulfur hexafluoride ($SF_6$), a non-reactive anthropogenic tracer which is released primarily from electrical distribution equipment with a spatial pattern characteristic of fossil fuel emissions, was chosen. Because the emissions and concentration field for $SF_6$ are much better known than for $CO_2$, the results of this "calibration experiment" were used to evaluate the realism of the large-scale inter-hemispheric transport characteristics of each model in a context for which the "right answer" was known. In addition, the calibration experiment included the calculation of transport diagnostics designed to help elucidate the mechanisms by which the various models produced their different tracer distributions.

Results from Phase II indicated closer model agreement than in Phase 1, partly due to a slightly different suite of models, and perhaps partly reflecting model improvement (Figure 3). One very significant conclusion is that the differences among the simulated north-south hemispheric gradients across models (which is used to interpret the strength of the meridional $CO_2$ sink in inverse calculations) depends very strongly on the details of the sub-grid scale vertical mixing. Again, the models could be classified into two categories: the first simulated relatively weak vertical gradients over the northern extra tropics ($SF_6$ source region), whereas the second group of models simulated stronger vertical gradients over the source region. This breakdown is likely the result of different model formulations with regard to how transport by convection and diffusion is parameterized at the subgrid scale.

The third phase of TransCom is presently underway and involves intercomparison of inversion calculations of the carbon budget of the atmosphere, with the objective of quantifying the uncertainty in such calculations that arises directly from uncertainty in the simulated transport. Computation of the contemporary carbon budget of the atmosphere using the suite of calibrated and improved models will provide both more reliable estimates of the terrestrial sink and a better set of tracer transport models for future research.

## GAIM in the future

The activities of the last few years have been directed toward laying the groundwork for the development of Earth System models of various levels of complexity. GAIM is now turning its attention to focus on Earth System Models of Intermediate Complexity (EMICs), and full-form Coupled Earth System Models, referred to as our "Flying Leap" to underscore the uncertainties and excitement of attempting to run fully coupled Earth System models into the future. While GAIM will continue the carbon cycle related subsystem model intercomparisons that have been its hallmark to date, its forays into the broader scope of Earth System modelling will require a higher level of integration of IGBP science than ever before. In response to this shift in emphasis, and by agreement of the Scientific Committee of the IGBP, GAIM has changed its name to Global Analysis, INTEGRATION, and Modelling.

Truly exciting times are ahead, as the efforts of the various parts of IGBP are brought together to form a coherent conceptualization of the Earth System. We are approaching a threshold in our abilities as a research community to address whole-system level problems, and the results that emerge in the next few years will surely contain some important answers to long-standing questions, and even a few surprises regarding the functioning of the Earth System.

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## Erratum

In the previous edition of the Global Change NewsLetter (Vol 40, December 1999) on page 15 we erroneously stated that the Global Environment Facility (GEF) was funded by the World Bank. This is not the case. The Global Environment Facility is independent of the World Bank and its funding does not come from the World Bank. We apologise for this error. The GEF is a multilateral financial mechanism that assists developing countries to protect the global environment in four areas: biodiversity loss, climate change, degradation of international waters, and depletion of the ozone layer. The GEF is jointly implemented by the United Nations Development Program, the United Nations Environment Program, and the World Bank.

...continued from page 11.

internal cycling. This P finds its way into the ocean and stimulates productivity there. At several points during the long slide into glaciation, pulses of aeolian Fe from the drying terrestrial biosphere further stimulate ocean productivity. Ice cover begins to advance as the climate cools and ocean circulation reorganises to its glacial state.

As cooling and drying proceeds, terrestrial biotic activity continues to decline, and the flux of nutrients from the land into the ocean eventually grinds to a halt. Oceanic uptake of $CO_2$ then starts to decline as well, and the system eventually reaches and bounces along its 'floor' at 180 ppm $CO_2$, effectively controlled by a quiescent terrestrial biosphere until the next cyclic change in the Earth's orbit jolts it back into the glacial termination phase and the whole intertwined loop of forcings and feedbacks starts over.

The cartoon in Figure 2 shows the suite of processes that link land and ocean biota in the control loops.

Again, the purpose of this explanation is not to provide the ultimate explanation of glacial-interglacial cycling; that will require much further work. Rather, we want to demonstrate the complexity of the issues we are facing and the absolute necessity of working across disciplines and 'compartments' to address them. The hypothesis put forward above could not have been developed by one discipline within the Earth sciences working alone. It required scientists from climatology, oceanography, geochemistry and terrestrial and marine ecology, and it required understanding of physical, chemical and biological processes.

The Stockholm workshop was evidence of the trend highlighted at the Second IGBP Congress at Shonan Village, Japan, earlier this year. Building on a sound base of compartment and process-level understanding in the core projects, we are now moving rapidly to build up expertise and activity in Earth System science, both in modelling and in analysis, as outlined in this article. This is truly a community effort, across all of IGBP. Both a sound understanding of basic processes AND the interactions and feedbacks among processes and compartments are required to even begin to understand the functioning of the Earth.

Finally, returning to the glacial-interglacial rhythm of the past 400,000 years, it is fascinating to put the very recent human perturbations to the Earth System in the context of this highly regular pattern. The current concentration of atmospheric $CO_2$ of 365 ppmV is well above the upper control limit of the Earth's recent past; there is no evidence of a stable state or 'domain of attraction' above about 280 ppmV. Furthermore, the rate of increase of atmospheric $CO_2$ is about two orders of magnitude larger than that during the glacial terminations. The rate of increase of mean global temperature over the past several decades also appears to be without precedent in the recent past (Mann et al. 1998). In terms of Earth's metabolism, we are sailing into *terra incognita*. Now more than ever, we must build a truly integrated, interdisciplinary Earth System science to understand the evolution of our planet and our role in it.

Extracted from: IGBP Carbon Working Group (2000) Integrated understanding of the global carbon cycle: A test of our knowledge. *Science*, submitted. IGBP Carbon Working Group: P. Falkowski, R.J. Scholes, E. Boyle, J. Canadell, D. Canfield, J. Elser, N. Gruber, K. Hibbard, P. Högberg, S. Linder, F.T. Mackenzie, B. Moore III, J. Raven, Y. Rosenthal, S. Seitzinger, V. Smetacek, W. Steffen.

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# The "Anthropocene"

by Paul J. Crutzen and Eugene F. Stoermer

The name Holocene ("Recent Whole")for the post-glacial geological epoch of the past ten to twelve thousand years seems to have been proposed for the first time by Sir Charles Lyell in 1833, and adopted by the International Geological Congress in Bologna in 1885 **(1)**. During the Holocene mankind's activities gradually grew into a significant geological, morphological force, as recognised early on by a number of scientists. Thus, G.P. Marsh already in 1864 published a book with the title "Man and Nature", more recently reprinted as "The Earth as Modified by Human Action" (2). Stoppani in 1873 rated mankind's activities as a "new telluric force which in power and universality may be compared to the greater forces of earth" [quoted from Clark (3)]. Stoppani already spoke of the anthropozoic era. Mankind has now inhabited or visited almost all places on Earth; he has even set foot on the moon.

The great Russian geologist V.I.Vernadsky (4) in 1926 recognized the increasing power of mankind as part of the biosphere with the following excerpt "... the direction in which the processes of evolution must proceed, namely towards increasing consciousness and thought, and forms having greater and greater influence on their surroundings". He, the French Jesuit P. Teilhard de Chardin and E. Le Roy in 1924 coined the term "noösphere", the world of thought, to mark the growing role played by mankind's brainpower and technological talents in shaping its own future and environment.

The expansion of mankind, both in numbers and per capita exploitation of Earth's resources has been astounding (5). To give a few examples: During the past 3 centuries human population increased tenfold to 6000 million, accompanied e.g. by a growth in cattle population to 1400 million (6) (about one cow per average size family). Urbanisation has even increased tenfold in the past century. In a few generations mankind is exhausting the fossil fuels that were generated over several hundred million years. The release of $SO_2$, globally about 160 Tg/year to the atmosphere by coal and oil burning, is at least two times larger than the sum of all natural emissions, occurring mainly as marine dimethyl-sulfide from the oceans (7); from Vitousek et al. (8) we learn that 30-50% of the land surface has been transformed by human action; more nitrogen is now fixed synthetically and applied as fertilizers in agriculture than fixed naturally in all terrestrial ecosystems; the escape into the atmosphere of NO from fossil fuel and biomass combustion likewise is larger than the natural inputs, giving rise to photochemical ozone ("smog") formation in extensive regions of the world; more than half of all accessible fresh water is used by mankind; human activity has increased the species extinction rate by thousand to ten thousand fold in the tropical rain forests (9) and several climatically important "greenhouse" gases have substantially increased in the atmosphere: $CO_2$ by more than 30% and $CH_4$ by even more than 100%. Furthermore, mankind releases many toxic substances in the environment and even some, the chlorofluorocarbon gases, which are not toxic at all, but which nevertheless have led to the Antarctic "ozone hole" and which would have destroyed much of the ozone layer if no international regulatory measures to end their production had been taken. Coastal wetlands are also affected by humans, having resulted in the loss of 50% of the world's mangroves. Finally, mechanized human predation ("fisheries") removes more than 25% of the primary production of the oceans in the upwelling regions and 35% in the temperate continental shelf regions (10). Anthropogenic effects are also well illustrated by the history of biotic communities that leave remains in lake sediments. The effects documented include modification of the geochemical cycle in large freshwater systems and occur in systems remote from primary sources (11-13).

Considering these and many other major and still growing impacts of human activities on earth and atmosphere, and at all, including global, scales, it seems to us more than appropriate to emphasize the central role of mankind in geology and ecology by proposing to use the term "anthropocene" for the current geological epoch. The impacts of current human activities will continue over long periods. According to a study by Berger and Loutre (14), because of the anthropogenic emissions of $CO_2$, climate may depart significantly from natural behaviour over the next 50,000 years.

To assign a more specific date to the onset of the "anthropocene" seems somewhat arbitrary, but we propose the latter part of the 18th century, although we are aware that alternative proposals can be made (some may even want to include the entire holocene). However, we choose this date because, during the past two centuries, the global effects of human activities have become clearly noticeable. This is the period when data retrieved from glacial ice cores show the beginning of a growth in the atmospheric concentrations of several "greenhouse gases", in particular $CO_2$ and $CH_4$ (7). Such a starting date also coincides with James Watt´s invention of the steam engine in 1784. About at that time, biotic assemblages in most lakes began to show large changes (11-13).

Without major catastrophes like an enormous volcanic eruption, an unexpected epidemic, a large-scale nuclear war, an asteroid impact, a new ice age, or continued plundering of Earth's resources by partially still primitive technology (the last four dangers can, however, be prevented in a real functioning noösphere) mankind will remain a major geological force for many millennia, maybe millions of years, to come. To develop a world-wide accepted strategy leading to sustainability of ecosystems against human induced stresses will be one of the great future tasks of mankind, requiring intensive research efforts and wise application of the knowledge thus acquired in the noösphere, better known as knowledge or information society. An exciting, but also difficult and daunting task lies ahead of the global research and engineering community to guide mankind towards global, sustainable, environmental management (15).

We thank the many colleagues, especially the members of the IGBP Scientific Committee, for encouraging correspondence and advice.

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# Contribution to the regional data bundle concept: The IGBP-DIS – MEDIAS-France partnership

by Wolfgang Cramer, Chair, IGBP-DIS

There is little doubt of the importance of the regional scale for Earth System Science and the need to study systemic features of Earth System functioning at that scale. A variety of tools are required for integrated regional studies, but a crucial element in the strategy is the development and application of regional 'data bundles'.

The concept of regional data bundles was first proposed at the 1998 DIS SSC meeting in Toulouse, and has now been developed further as a major activity aimed at promoting an integrated suite of regional studies. The implementation of the regional data bundle concept will be undertaken, *inter alia*, as a partnership between IGBP-DIS, START and MEDIAS-FRANCE.

Regional data bundles consist of a consistent collection of databases, data products, in-situ measurements as well as remotely sensed data. Data bundles may include models and/or model output at regional scale. Special attention is given to the presentation of the various data sets in order to facilitate their visualization and interpretation for research purposes.

Considerable work on regional databases has already been undertaken in association with IGBP:

- The Miombo CD-ROM, coordinated by START, LUCC and IGBP-DIS, is an early version of a regional data bundle but is essentially a 'one-off'.
- LBA (the Large-scale Biosphere-Atmosphere Experiment in Amazonia) has its own data and information system, well developed and a good model for other large regional studies.
- Specific data functions have been established in some START regional secretariats, such as Nairobi (Pan-African) and Bangkok (Southeast Asia).
- The IGBP Terrestrial Transects have developed their own data sets.

However, these initiatives are largely independent of one another, making comparability across regions virtually impossible. What is needed now is coordination of these data activities to build up a coherent global picture from the various regional studies. This requires much more consistency and coherence across the various data initiatives, as well as a common framework for process studies and modelling.

MEDIAS-FRANCE is well placed to contribute to the implementation of a coordinated approach to the regional data bundle initiative. MEDIAS has acted as a regional coordinating secretariat for START, acting through projects funded by the EU's ENRICH programme and through the START Fellowship/Visiting Scientist Programme. MEDIAS also works in close cooperation with PASS (Pan African START Secretariat), its counterpart regional structure in Africa.

In addition, MEDIAS-FRANCE is already involved with several IGBP core projects – PAGES, JGOFS, IGAC - to develop computer tools for the generation of new databases for IGBP research projects. More recently, MEDIAS-FRANCE has been asked by IGAC to develop an original tool to assist its Synthesis and Integration project. MEDIAS also maintains a "mirror" site of the global PAGES database belonging to the World Data Center-A for paleoclimatology in Boulder, USA.

Based on these existing strengths of MEDIAS, its experience in regional data development, and its knowledge of IGBP, the French space agency CNES has offered to allocate resources via MEDIAS to support a major effort over the next 2-3 years to produce a coherent set of regional data bundles. IGBP-DIS will provide guidance for the effort, and will rely on input from START, GAIM and the core projects, many of which have their own sets of regional studies.

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# People and events

Neil, right, farewells his colleagues João Morais and Elise Wännman during his last day in the Secretariat.

## Neil Swanberg Sails On…….

An era in IGBP ended recently with the resignation of Neil Swanberg from his position of Deputy Executive Director, to take up a position with the National Science Foundation in the United States.

Neil joined the IGBP Secretariat in 1993, while the programme was still in its early implementation phase. He has served under all three Chairs (Jim McCarthy, Peter Liss and Berrien Moore) and under all four Executive Directors (Thomas Rosswall, John Marks, Chris Rapley and Will Steffen).

For the past seven years, Neil has been a mainstay and pillar of strength in the IGBP Secretariat. He has helped to keep the office ticking over efficiently, has become a master at trouble-shooting (often anticipating problems before they occur), dealt effectively with bureaucracies on both sides of the Atlantic, and navigated our small Macintosh computer network throughout the sometimes turbulent waters of a PC-oriented host institution.

I'm sure one of Neil's biggest frustrations has been trying to cope with computer-illiterate colleagues in the Secretariat making big computer problems out of small ones. He has always dropped whatever he is doing to come to the aid of his co-workers and has invariably solved problems quicker than professional computer consultants could manage. Only one incident stopped Neil – a beer-soaked keyboard and disk drive on a certain laptop – but that is another story……

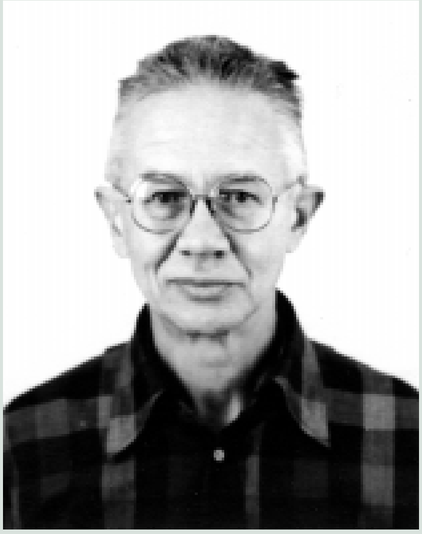
Neil was particularly well-known in the marine components of IGBP. He is a marine biologist by training, and that coupled with his broad understanding of international science has enabled him to make valuable contributions to JGOFS, LOICZ and, more recently, GLOBEC and SOLAS. In fact, Neil played an instrumental role in working with the GLOBEC community to guide the development and publication of both the science and implementation plans. His nous and understanding both of the science and the science politics in international marine science has been a major factor in the smooth transition now underway within the oceanic components of IGBP.

Perhaps Neil's least known contribution to IGBP, but his most important, has been his broad understanding of the programme as a whole and his vision for where IGBP should be going. His article in NewsLetter 40 is a good summary of his views on how the pieces of the puzzle should fit together. But this view has been characteristic of Neil for quite some time. Well before the recent push in the Programme towards a more integrated Earth System Science approach, Neil has been quietly but effectively promoting a more systemic and logical structure and approach for IGBP's science. The process is now coming to fruition, and he has made strong and consistent intellectual contributions to it over a number of years.

Neil has always maintained that about five or six years is long enough in the job. So he leaves IGBP in the spirit of 'job well done' and of making major contributions to a complex scientific endeavour.

All of us throughout the IGBP community wish Neil, his lovely wife Inger and their two lively sons, Kevin and Carl, all the very best for their life in the US.

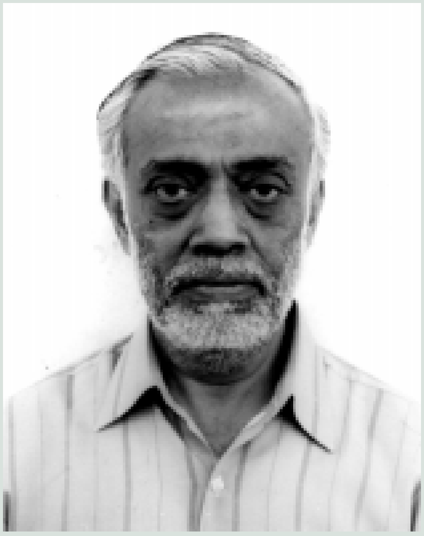
## New members of the Scientific Committee of the IGBP



Upon graduating from Leningrad State University, Faculty of Physics, in 1953, **Victor Gorshkov** worked in the field of physics of elementary particles, high-energy physics and atomic physics, with about 60 papers published in leading journals. At present, he is Professor of Theoretical Physics and works in Petersburg Nuclear Physics Institute, St.-Petersburg, Russia.

In the early eighties Victor gradually turned to global ecological problems, being impressed by their importance and by the potential impact that the theoretical physics approach may have there. Having accomplished several studies in such diverse fields as the global carbon cycle, ecology of locomotive animals, evolutionary genetics and informatics, Victor formulated the concept of biotic regulation of the environment, a concept around which his own work and that of his group is devoted (see, e.g., Gorshkov et al. (2000) Biotic Regulation of the Environment: Key Issue of Global Change. Springer, Praxis).

In his free time, Victor enjoys field research in the wilderness areas of Siberia and the north of European Russia. Closer to home, he often enjoys a keen game of tennis.



**S. Krishnaswami** was born and brought up at Thiruvananthapuram, the southernmost city of India. He received his B.Sc. degree in chemistry from the University College, Thiruvananthapuram. He began his research career in 1964 at the Tata Institute of Fundamental Research, Bombay and obtained his Ph.D. degree in 1974 from the Bombay University. A part of his thesis was on the successful development of $^{210}$Pb method to date lake sediments, which has found extensive applications to chronologically decipher historical records of natural and anthropogenic events stored in them.

Krishnaswami is a geochemist, focusing on the applications of environmental isotopes, stable and radioactive, to study earth surface processes. His interests include solute-particle interactions and particle dynamics in the ocean, sedimentation and authigenic mineral formation in the lakes and deep sea, nuclide mobility (contaminant transport) in sub-surface aquifers and more recently chemical weathering of the Himalaya and its impact on the chemical and isotopical budget of the oceans.

Currently, Krishnawami is a professor at the Physical Research Laboratory, Ahmedabad, where he has been working for the past 25 years. He has served as a member of the JGOFS SSC and as one of the Vice-Presidents of SCOR. This year he was elected as one of the Vice-Presidents of IAPSO.

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