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Geocybernetics: Controlling a Complex Dynamical System Under Uncertainty

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Global change, i.e. the mega-process radically transforming the relationship between nature and human civilization since the end of World War II, is investigated from the point of view of systems analysis. It is argued that this unbridled process should rather be domesticated by planetary control strategies transpiring from a new science called "geocybernetics". The formal aspects of geocybernetic theory are sketched and illustrated in a tutorial theatre world reflecting the overall environment and development problematic. Within this setting a straightforward operationalization of the sweeping "sustainable development" ideal through a set of concise paradigms can be achieved. Evidence is provided that geocybernetics is actually feasible on the basis of earth system modelling and fuzzy-control techniques.

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Introduction: What Geocybernetics Is All About

Consider the following chronological sequence of events:

E1. Autumn 1987: 42th UN General Assembly: Gro Harlem Brundtland, Chairperson of the World Commission on Environment and Development, presents its report "Our Common Future" to the public (WCED 1987).
E2. July 1992, Germany: a girl is swaying back and forth on a garden swing.
E3. May 1995, Pacific Ocean west of the Galápagos: members of the "IronEx II" mission dump 500 kg iron sulphate into the tropical sea (Coale et al. 1996).
E4. August 1997, USA: Tziperman et al. 1997 publish a paper on "El Niño" modelling in *Physical Review Letters*.

Do these events have anything in common? They do indeed (as we shall explain in some detail below) – by highlighting crucial aspects of that grand challenge humankind will have to face and to master in the millennium ahead, namely global environment and development (E & D) management. Such a management means nothing less than to plan, bring about and sustain an acceptable long-term coevolution of nature and civilization on planet earth (Clark 1989). The scientific basis still to be created for tackling such a formidable (unfeasible?) task may be called *"geocybernetics"*, i.e. the art of adequately controlling the complex dynamic earth system under uncertainties of all kinds.

At this point the reader may be tempted to classify the authors of this article as jokers, dreamers or lunatics. Before stop reading, however, we urge to realize that some sort of global E & D management, although largely without rhyme or reason, is already in full progress. There is, on the one hand, the perpetually accelerating process of "globalization" as driven by the teleconnected forces of economy, technology and life-style. This process is pushing forward the material development of many countries, yet transforms the ecological and cultural (sur)face of our planet in an unprecedented "*global change*" (Pfister 1994, WBGU 1994). On the other hand there is the process of "global environmental policy" that tries to repair or prevent the presumably unpleasant side effects of global change through a system of international conventions, protocols and regulations (Soroos 1994, Johnston 1995, Wapner 1995, Lafferty 1996). The most stunning illustration of this process is the "ozone diplomacy" (Benedick 1991) for preserving the earth's stratospheric shield against UV-B radiation: based on reasonable, but hardly perfect scientific evidence on atmospheric chemistry under extreme conditions (Graedel and Crutzen 1989, Toon and Turco 1991), the Montreal protocol and its amendments cold-bloodedly determine and enforce the CFC emissions reductions just sufficiently to avoid a planetary catastrophe. Some 50 years from now we will be able to tell whether this act of ecosphere management was actually successful.

Thus there are plenty of global E as well as D measures, but they are almost unrelated in spite of the call for their orchestration made in the documents of the "Earth Summit" in Rio in 1992 (UNCED 1992). And the potential manual of global E & D management, the Agenda 21, is rather an eclectic compilation of innocuous (or elusive) targets than the blueprint for a grand planetary strategy. Yet that state of affairs must be overcome, and it is geocybernetics that will probably prove indispensable in fulfilling this task. This science *in statu nascendi* will differ both from *geography*, which contemplates an intangible world, and from "*geoengineering*" (see below), which believes in straightforward technical fixes for all the predicaments generated by the triumphant march of Western civilization around the globe.

We try to outline here the pertinent features of what geocybernetics ultimately may become in the following pages. This article is based on a lecture given by one of the authors (H.J.S.) at the Munich Physics Colloquium; for a detailed account of geocybernetics see the forthcoming book *Earth System Analysis: Integrating Science for Sustainability*, edited by Schellnhuber and Wenzel 1998.

Global Change: Why Geocybernetics Is Mandatory

From the global perspective, humanity has been a "free rider" on nature's bandwagon until very recently. The turning point is actually marked by the end of World War II, which established a novel political and socio-economic regime on this planet, and thereby brought about "global change". The previous relationship between the *ecosphere* $\mathcal{N}$ and the *anthroposphere* $\mathcal{A}$ may be formalized in the following, utterly simplified manner:

$$\begin{aligned}\dot{\mathbf{N}}(t) &= F_0(\mathbf{N}; t)\\ \dot{\mathbf{A}}(t) &= G_0(\mathbf{N}, \mathbf{A})\end{aligned} \tag{1}$$

Here t stands for the time variable and a dot symbolizes the time derivative. The mathematical entities **N** and **A**, which will not be specified here, represent the macro-states of $\mathcal{N}$, (i.e. the total natural environment of significance for humanity) and $\mathcal{A}$ (i.e. humanity along with all of the products of its civilization), respectively. Equation 1 describes the temporal development of the $\mathcal{N} - \mathcal{A}$ complex; as with the simplest dynamic systems, we assume that the first time derivatives of the individual macro-variables can essentially be calculated as functions of the momentary state of all variables. The necessary mathematical prescriptions are designated here as F_0 and G_0.

The message encoded in Eq. 1 is unequivocal: the temporal evolution of the ecosphere formerly depended on its momentary state only, perhaps complemented by exogenous influences (e.g. asteroid impacts) as expressed by the explicit time dependence of F_0. Thus the natural dynamics was completely decoupled from the anthroposphere's evolution, which constituted a negligible perturbation at the earth system's scale.

In these times of global change, however, a dramatically different picture is emerging, since civilization is now interfering significantly with the metabolism of $\mathcal{N}$. One of the most conspicuous examples of this interference is the anthropogenic enhancement of atmospheric CO_2 (see Fig. 1), which represents one of the key factors determining the global climate dynamics. Let us quote just a few

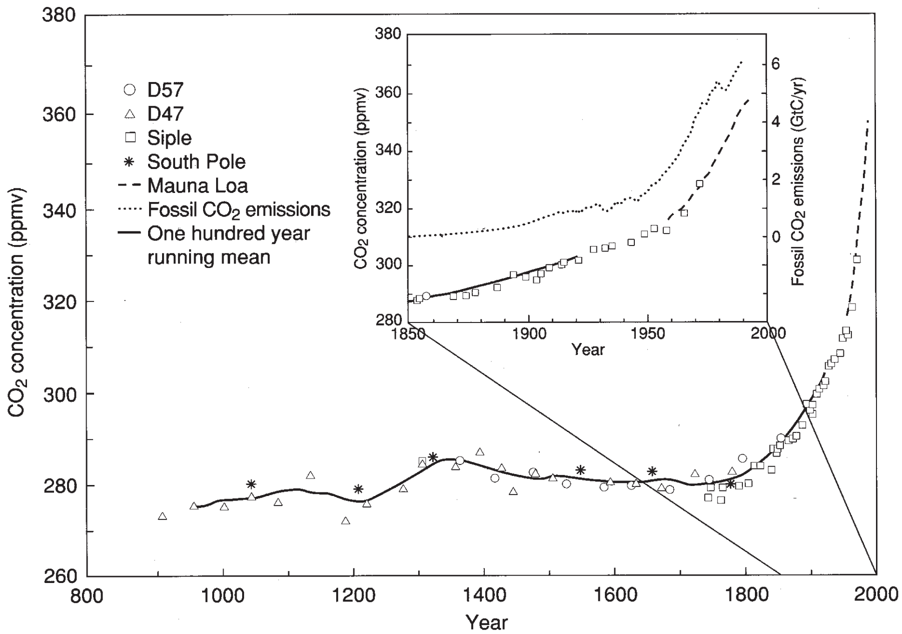

Fig. 1. CO_2 concentrations over the past 1,000 years from ice core records (D47, D57, Siple and South Pole) and (since 1958) from Mauna Loa, Hawaii, measurement site. All ice core measurements are taken in Antartica. Note that the human impact really explodes in the middle of the 20th century. From Houghton et al. (1996)

figures in order to characterize other environmental aspects of the planetary success story of modern civilization (see also WI 1984–1997, WRI 1986–1997, SCOPE 1971–1997, WBGU 1993–1997):

- The volume of continental freshwater at present retained by artificial dams amounts to five-fold that of all the rivers of the earth (e.g. Chao 1995).
- Since World War II, close to 30% of the world's arable land has been abandoned (Lal and Stewart 1990), and worldwide approximately 120,000 km^2 per year are destroyed by mostly anthropogenic erosion and other forms of degradation (Pimentel 1997).
- Humanity now manipulates approximately 40% of the net primary terrestrial production caused by green plants (Wrigth 1990).
- The decadal rate of anthropogenic caused species extinction is estimated to be within the range of 1–5% (McNeely et al. 1995).

This list, which may easily be continued, clearly demonstrates that civilizatory perturbations already act on a planetary scale and are about to change the qualitative character of the ecosphere's operating mode. Thus the formal description of the dynamics of the $\mathcal{N} - \mathcal{A}$ complex by Eq. 1 must be replaced by the following equation of motion:

$$\begin{aligned} \dot{\mathbf{N}}(t) &= F_1(\mathbf{N}, \mathbf{A}; t), \\ \dot{\mathbf{A}}(t) &= G_1(\mathbf{N}, \mathbf{A}). \end{aligned} \tag{2}$$

All symbols have the same meaning as in Eq. 1; only the index of the functions F and G has been properly modified. Equation 2 explicitly treats ecosphere and anthroposphere as equivalent, strongly coupled cofactors of planetary evolution. The problems arising from such an intimate and involved relationship are obvious.

Note, however, that the really big E & D challenges have yet to be tackled. Consider, for instance, the energy issue: in order to provide the roughly 10 billion people predicted to live on earth in the year 2050 with the energy options currently available in, say, Portugal, the world wide power supply must be amplified by (at least) a factor of 10 . As fossil fuel stocks are limited, although sufficient to "achieve" significant climate destabilization, the problem might only be solved by a resolute switch to renewable energy sources. As a matter of fact, the Shell company recently announced investments of US$ 500 million over the next five years in photovoltaic and biomass R & D activities, as the company expects the renewables to account for more than 50% of the world energy generation by the middle of the next century. Such an industrial revolution of the third kind requires, however, a thoroughly renewed division of labour between the potential producer countries of the equatorial sunbelt and the technology strongholds aligned around the poles. An alternative (or, most probably, complementary) approach would be to tap the greatest energy resource of all, namely the "neg-energy" provided by considerably enhanced procedural and behavioural efficiency. In view of the continued adoption of "Western" lifestyles and consumption patterns by the developing world, such an approach will fail without a well-organized global exchange of technology and wisdom, which should be funded mainly by the OECD countries.

Another crucial global-scale issue is the biodiversity – food production – human well-being complex: in this context, we are currently witnessing an absurd planetary dynamics, which converts the tropical and sub-tropical genetic treasure houses into (at best) mediocre agricultural areas, while the high-yield countries of the temperate zones desperately try to preserve their (comparatively negligible in numbers) remnants of endogenous species through complicated portfolios of regulations. A wise global E & D strategy should work precisely the other way round: feed the world via a fair, deregulated and efficient international agro-market based on the sustainable production of the naturally favoured regions far from the equator (or high above mean sea level), and establish the hot and sunny terrestrial regions of this planet (e.g. the tropical rainforest domains or the Sahel zone) as "biosphere reserves" supporting genetic pools as well as soft tourism, recreation, urbanization and even high-tech industry. This strategy might be sophisticated by *responsible* use of molecular biology, that will soon have all life on earth at its disposal, in principle, as the President of the German Science Foundation (DFG) recently put it.

Ideas of this kind may appear rather utopian to most people as yet, but they simply account for the distribution of "comparative advantages" over the globe and for the exploding stock of options as provided by scientific progress. True global E & D management must not shy away from these considerations, if the coevolution task is to be accomplished. It is, in fact, time to start acting in a geocybernetic way that replaces the incoherent global assortment of local short-term optimization schemes. The aspired "geocybernetic age" will be characterized by the following symbolic dynamics:

$$\begin{aligned}\dot{\mathbf{N}} &= F_2(\mathbf{N}, \mathbf{A}; t; \mathbf{M}(t))\\ \dot{\mathbf{A}} &= G_2(\mathbf{N}, \mathbf{A}; \mathbf{M}(t))\end{aligned} \tag{3}$$

where $t \geq 0$, as we identify the origin of the time axis with the present.

Equation 3 differs from Eq. 2 (describing contemporary global change dynamics) in one crucial aspect, namely the inclusion of an external control function $\mathbf{M}(t)$ that may vary in time. $\mathbf{M}$ represents an arbitrary element of a pool $\mathfrak{M}$ of coherent voluntary management strategies at the disposal of the "global subject". The latter entity, a modern and rather profane realization of Hegel's *Weltgeist*, is about to emerge from the world-wide web of communications and interactions under the additional pressure of thousands of supra-national non-governmental organizations (Brodribb 1997). Its recent grand entrance at the Rio conference will undoubtedly be followed by even more spectacular performances in the decades to come. A given strategy $\mathbf{M}(t)$ consists of a carefully selected sequence of available E & D measures that can be activated: regulatory law, economic incentives, educational or instructional programmes, international agreements, campaigns by global institutions such as the organs of the UN.

Thus the dynamics of the $\mathcal{N} - \mathcal{A}$ complex depends sensitively on the choice of $\mathbf{M}$: the coevolution paths $\mathbf{P}(t \mid \mathbf{M}) \equiv (\mathbf{N}(t \mid \mathbf{M}),\ \mathbf{A}(t \mid \mathbf{M}))$ generated by different management sequences will generally diverge. In other words, the future of the earth system is to be picked from an infinite bundle of optional coevolution paths. One should not forget, by the way, that the "nuclear winter" option (Svirezhev 1987, Turco and Golitsyn 1988) was discarded only very recently ! In summary, we are today confronted with an awesome (and awful) control problem of intimidating complexity. Exercising this control means to answer the following fundamental questions of geocybernetics (Blackburn 1992).

- What kind of world do we have ?
- What kind of world do we want ?
- What must we do to get there ?

We will try to examine these questions in the remainder of this paper.

Ecosphere Modelling: What Geocybernetics Is Based Upon

Starting, with the first key question – what kind of world do we have ? – we focus almost exclusively on the ecosphere, i.e. the biogeophysicochemical machinery supporting human civilization. To monitor, understand and model this complex non-linear dynamic system is actually the sweeping objective of

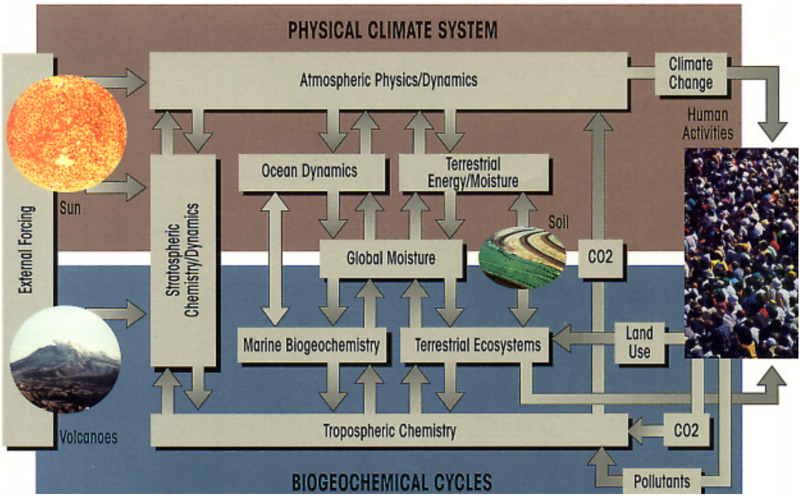

Fig. 2. A simplified version of the famous Bretherton diagram, displaying the basic "physiology" of $\mathcal{N}$. (From CIESIN 1992)

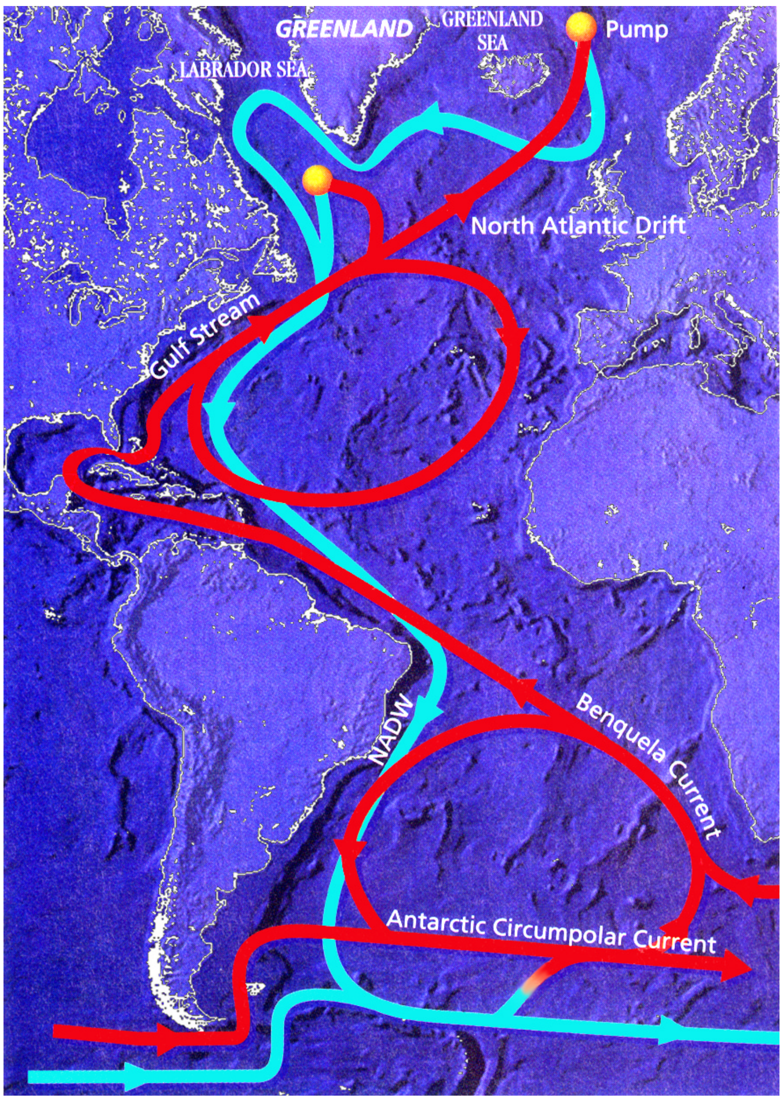

Fig. 3. The Atlantic Ocean "conveyor belt". Two "pumps" in the Labrador Sea and the Greenland Sea, respectively, generate a cold deep-sea current (*blue ribbons*) which is ultimately transformed into a warm surface stream (*red ribbons*) that closes the marine thermohaline dynamics. (From Rahmstorf 1997)

a highly ambitious world-wide and transdisciplinary scientific enterprise in progress, namely the “International Geosphere-Biosphere Programme” (IGBP 1994, 1997). IGBP ultimately intends to generate a united (“holistic”) picture of its subject by gradually working out the concrete parts and pieces as defined by Bretherton’s schematic wiring diagram (for a detailed version see Mosaic, vol. 19, no. 3/4, 1988; National Science Foundation) of the ecosphere (Fig. 2). The achievements of IGBP and related activities are already impressive. It seems, in particular, that a solid scientific basis for comprehensive *simulation modelling* of the ecosphere will emerge in the coming years. And simulation modelling is a *conditio sine qua non* for geocybernetics: as we are endowed with just one earth system specimen, we are not entitled to many real global experiments with it. We may, however, resort to “geo-cyberspace”, where virtual copies of $\mathcal{N}$ can be exposed to virtual perturbations (like CO_2 quadrupling or eradication of all tropical rainforests).

Most of the simulation models currently available for playing this digital game (with a most serious background) refer to certain sub-modules of the total ecosphere, though. A quite topical example is provided by the successful description and even prediction of the “El Niño–Southern Oscillation” (ENSO) phenomenon that involves an irregularly occurring warming of the equatorial Pacific triggering a cascade of severe ecological and socio-economic impacts around the globe (Philander 1989, Latif et al. 1994, Knutson and Manabe 1993). The paper by Tziperman et al. (1997) mentioned above (E4) elaborates on the possible modelling approach to ENSO, which relies on the theory of chaotic dynamic systems. A major achievement of this theory has been the discovery that chaos-prone non-linear systems may be controlled, in spite of their intricacy and at least theoretically, by rather robust and simple methods (e.g. Ott et al. 1990; Shinbrot 1995; Ding et al. 1996). In a remarkably bold undertaking, Tziperman and his colleagues extend these methods appropriately and apply the results to their ENSO models. As a consequence, they generate an explicit scheme for taming Niño’s caprices through clever modification of the Kelvin mode amplitude at the western equatorial boundary of the Pacific! Although the proposed feedback-control exercise is clearly restricted to the model universe at present, this work indicates where geocybernetics may be heading in the not-too-distant future (see also “Outlook”).

Whether we consider total or partial simulation models of $\mathcal{N}$, three major types can be identified. We discuss each class briefly, and illustrate it with an example from the immediate scientific environment of the authors at the Potsdam Institute.

Tutorial Models

These models mainly serve as “geo-cyberspace toys” that help us, on the one hand, to train our skills for the rough climate of the “serious” simulation world and, on the other hand, to explore fundamental effects and phenomena in the system under investigation. An ingenious representative of the tutorial type is the famous Daisy World model (Watson and Lovelock 1983) which was devised to support the so-called Gaia hypothesis (Lovelock 1991) on the self-stabilization of the biosphere. The Daisy World toy demonstrates how insolation-albedo-growth feedback on an utterly simplified bioplanet establishes highly stable environmental conditions. A considerably sophisticated two-dimensional version of the original model corroborates this fundamental observation, but shatters the familiar belief that genetic diversity enhances the resilience of an ecosystem (von Bloh et al. 1997).

Conceptual Models

The models in this class generally attempt to catch the spirit of the original in its entity, but not necessarily to reproduce the metric proportions of the real counterpart. Therefore, in the best case, the modelling activity creates a caricature which is sometimes more recognizable than its subject. The caricature does not even have to preserve the dimensionality of the system in question: under certain conditions even zero-dimensional simply-wired box models may successfully simulate the qualitative behaviour of “the real thing”. Conceptual modelling is very useful for the investigation of the world-wide thermohaline oceanic circulation organized in some sort of “conveyor belt” (Broecker 1995). This dynamic pattern is driven by massive deep-water formation in the North Atlantic (see Fig. 3) and supports the Gulf Stream as a minor offspring. Rather simple box models are capable of describing the overall phenomenon satisfactorily and even demonstrate that the conveyor belt may be weakened or even shut down by changes in the global hydrological cycle via dilution effects (Rahmstorf 1995). Such an event, which dramatically affects the European climate, has evidently been realized in history many times and could be triggered again by anthropogenic global warming (Houghton et al. 1996, Rahmstorf 1997a). Conceptual models of the thermohaline circulation provide a remarkably efficient testbed for exploring this type of threat associated with global change well in advance.

Analogical Models

Models of this type try to mimic, as far as necessary or possible, the total dynamic ecosphere or at least large segments of it. Analogical modelling is currently still focused on three-dimensional copies of the coupled ocean-atmosphere circulation system which are electronically animated according to mathematical prescriptions such as partial differential equations or cellular-automata rules. There is an increasing trend, however, to generate more realistic simulations of the ecosphere true to scale by integrating sub-models representing biospheric and pedospheric elements. It now seems clear that *the* big enigma of ecosphere analysis, namely the global glaciation episodes as triggered by minor modulations of the parameters characterizing the earth's motion around the sun (Milankovich forcing), can be solved only by such means.

Simulation modelling of the analogical kind is an extremely laborious and resource-consuming enterprise often transcending the capacities of smaller research groups. It may not even be the most intelligent way to conduct "earth system analysis", as the really pertinent mechanisms ruling ecosphere dynamics might be swamped by vast quantities of irrelevant output data. If used properly, however, analogical models open the door to a cosmos of fantastic new insights into the metabolism of $\mathcal{N}$. This is nicely illustrated by recent simulations of the Sahara-Sahel vegetation cover over the past 25,000 years with models coupling state-of-the-art atmospheric and biospheric components (Claussen and Gayler 1997, Ganopolski et al. 1998, Kubatzki and Claussen 1998). The calculations show that the Sahara-Sahel region may generally assume two markedly different bio-states, namely a "green" and a "barren" one. This bi-stability transpires from a subtle interplay between insolation as controlled by orbital parameters, African monsoon, and geophysical characteristics of the respective vegetation cover (e.g, Claussen 1997, Claussen et al. 1998). As a matter of fact, a greening of northwestern Africa would be a feasible and stable option under contemporary natural conditions !

While this brief taxonomy of ecosphere modelling is rather encouraging, we must confess that the picture looks much more bleak when it comes to simulation of anthropospheric elements (see the tangling box "human activities" in Fig. 2). There are signs of hope, however, that even this delicate field is becoming gradually accessible to formal dynamic imitation. The scientific methodologies to be used there will transcend the ones employed in ecosphere simulation in intricacy and sophistication; just think of evolutionary economics, multi-actor game theory, social synergetics, etc. We refer the reader to pioneering *"integrated modelling"* activities concerning global change issues, such as, for instance, the Image approach (Alcamo 1994) and the Targets approach (Rotmans and de Vries 1997). A new kind of qualitative modelling of the entire $\mathcal{N} - \mathcal{A}$ complex may ultimately emerge from the "syndromes analysis" put forward by the German Advisory Council on Global Change (WBGU 1997; Schellnhuber et al. 1997).

Sustainable Development: What geocybernetics is striving for

Having gained, in the preceding section, a somewhat optimistic perspective on our efforts to understand the mechanisms governing particularly the physical part of the earth system, we are confronted with the fundamental question about the use we wish to make of this wisdom: what kind of world do we want ? In other words, the objectives, or even better, the *paradigm* for conscious and responsible coevolution control has to be distilled from the preferences of the "global subject", who in turn is supposed to represent the volitions of billions of individuals today and tomorrow.

A sweeping, but somewhat elusive solution to this problem has been suggested by the Brundtland Re-

Table. 1. Notation and qualification of the five fundamental SD paradigms

Symbol	Name of paradigm	Positive goal	Negative motive
$\mathcal{P}_0$	*Standardization*	*Order*	*Despotism*
$\mathcal{P}_1$	*Optimization*	*Prosperity*	*Greed*
$\mathcal{P}_2$	*Pessimization*	*Security*	*Cowardice*
$\mathcal{P}_3$	*Equitization*	*Fairness*	*Jaundice*
$\mathcal{P}_4$	*Stabilization*	*Reliability*	*Indolence*

port mentioned above (E1): "sustainable development" (SD), i.e. a co-evolution "that meets the needs of the present without compromising the ability of future generations to meet their own needs". This motto is so vague that almost every actor in the global E & D game can subscribe to it in order to benefit from the positive connotation. What is even worse is that everyone seems to feel entitled to put forward his/her own self-serving interpretation of SD. A thorough survey of the existing literature on this topic and a rigorous structural analysis reveal that the fuzzy SD maxim can be decomposed into a set of crisp independent paradigms with well-defined underlying operational principles. The result of this exercise in "mathematical ethics" is presented in Table 1. A detailed discussion of all these paradigms would be beyond the scope of this article; we restrict ourselves to indicating, at least, the essence of the probably most unfamiliar coevolution strategies listed above, namely, *"pessimization"* and *"equitization"*. The remaining three paradigms are actually more conventional, but by no means trivial SD interpretations: *"standardization"* basically means strict compliance with external normative settings, *"optimization"* strives to maximize a somehow defined integrated welfare function over a certain time interval, and *"stabilization"* aims at landing spaceship earth softly in an acceptable (generalized) equilibrium state.

It turned out that the best setting for explaining the spirit of distinct SD paradigms is provided by a two-dimensional "theatre world" caricaturing the real coevolution control task. A possible realization of this is introduced in Fig. 4. It may be interpreted as follows. The **N**-axis is the scale for the state of the global climate, while the **A**-axis measures the degree of development of human civilization (in terms of gross global product or the like). Then the structure of our metaphorical coevolution plane is governed by the existence of an *"ecological niche"* for life in general and humanity in particular (e.g. Kasting et al. 1988, Franck et al. 1998). This niche is sub-divided between the "Martian regime", where a "runaway cooling chamber process" invariably drives the ecosphere towards the "Martian fixed mode" (*MFM*) of planetary operation, and the "Venerian regime", where a "runaway greenhouse process" invariably drives the ecosphere towards the "Venerian fixed mode" (*VFM*). Thus *MFM* and *VFM* symbolize asymptotic ambient states reflecting the conditions now prevailing on our neighbour planets. Starting from the present state of the earth system, $\mathbf{P}_0$, somewhere within the ecological niche, the "global subject" can choose among a multitude of possible coevolutionary courses as realized by the distinct management sequences assembled in $\mathfrak{M}$. The *"accessible universe"*, $\mathfrak{U}(\mathbf{P}_0)$, which is the set of all coevolutionary states attainable in the course of time through appropriate steering, does not fill the entire civilization-supporting niche within our illustrative theatre world. $\mathfrak{U}(\mathbf{P}_0)$ embraces, on the other hand, *"catastrophe domains"* that constitute gates to Martian or Venerian hell. We generally call some sub-set of coevolution space a catastrophe domain, if this sub-set is (a) accessible from $\mathbf{P}_0$, (b) composed of strictly intolerable states for humanity (according to certain standards), and (c) inescapable by all means of E & D management. Thus the geocybernetic task is clearly defined within the framework of our extremely simplified coevolution game: pick a control option $\mathbf{M}^* \in \mathfrak{M}$ that warrants coevolution in accordance with the preferred SD paradigm, which obviously means steering clear of catastrophe pockets in the first place !

Pessimization

By way of contrast to "optimization" strategies that aim for the maximum benefit in spite of often considerable risks, the "pessimization" paradigm (denoted $\mathcal{P}_2$ in Table 1) strives for the greatest possible safety vis-à-vis potential human failures and whims of nature. Therefore, $\mathcal{P}_2$ strategies may be qualified

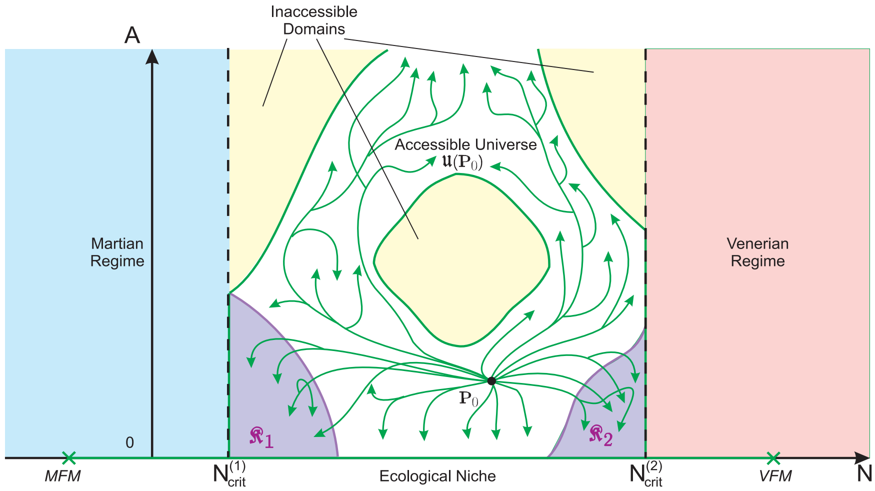

Fig. 4. A toy world for epitomizing fundamental SD strategies. The coevolution space embracing all conceivable coevolution states $\mathbf{P} = (\mathbf{N}, \mathbf{A})$ is spanned by a natural and a civilizatory axis. Vertical lines $\mathbf{N} = \mathbf{N}_{\mathrm{crit}}^{(1)}$ and $\mathbf{N} = \mathbf{N}_{\mathrm{crit}}^{(2)}$, respectively, delimit the niche of subsistence states for humanity within the overall coevolution space. The domain $\mathfrak{U}(\mathbf{P}_0)$ (*green*) embraces the set of all possible coevolution states that can be reached from the present ($t = 0$) state $\mathbf{P}_0 = (\mathbf{N}_0, \mathbf{A}_0)$ by appropriate management sequences $\mathbf{M} \in \mathfrak{M}$. $\mathfrak{U}(\mathbf{P}_0)$ contains specific sub-sets $\mathfrak{K}_1$ and $\mathfrak{K}_2$, qualified as "catastrophe domains"

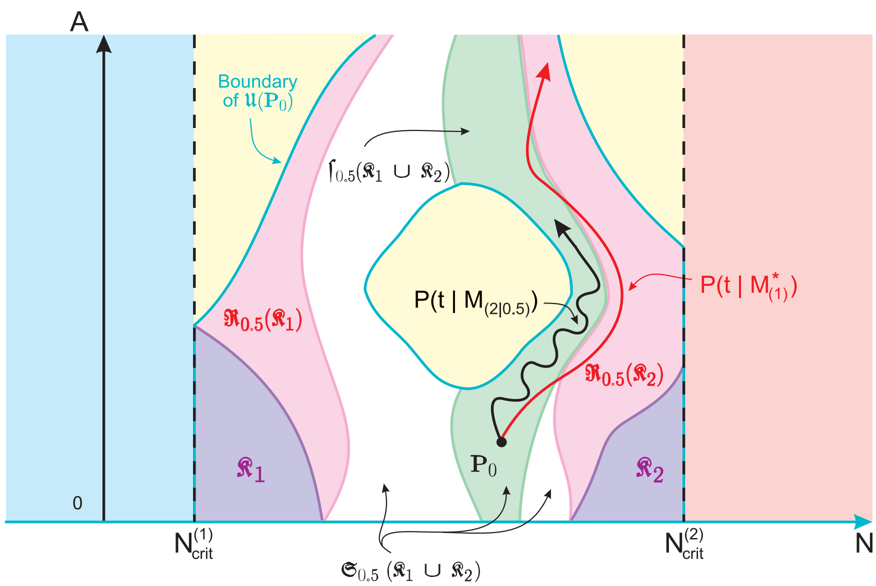

Fig. 5. Cartoon of weak anti-Murphy strategy for $\hat{x} = 0.5$. The 0.5 safety zone $\mathfrak{S}_{0.5}$ refers to the union of catastrophe domains, $\mathfrak{K}_1 \cup \mathfrak{K}_2$ (while $\mathfrak{s}_{0.5}$ represents a particular sub-set of $\mathfrak{S}_{0.5}$ irrelevant for the specific illustration of $\mathcal{P}_2$ intended here). A potentially "optimal" (with respect to certain E & D criteria) coevolution path $\mathbf{P}(\mathbf{t} \mid \mathbf{M}^*_{(1)})$ is drawn in for comparison; it trespasses into the 0.5 risk environment at least twice and is therefore forbidden by the pessimization paradigm. By way of contrast, the management $\mathbf{M}_{(2|0.5)}$ steers the "earth system" as safely as required through coevolution space, although the "progress" associated with the so-generated path may be rather slow

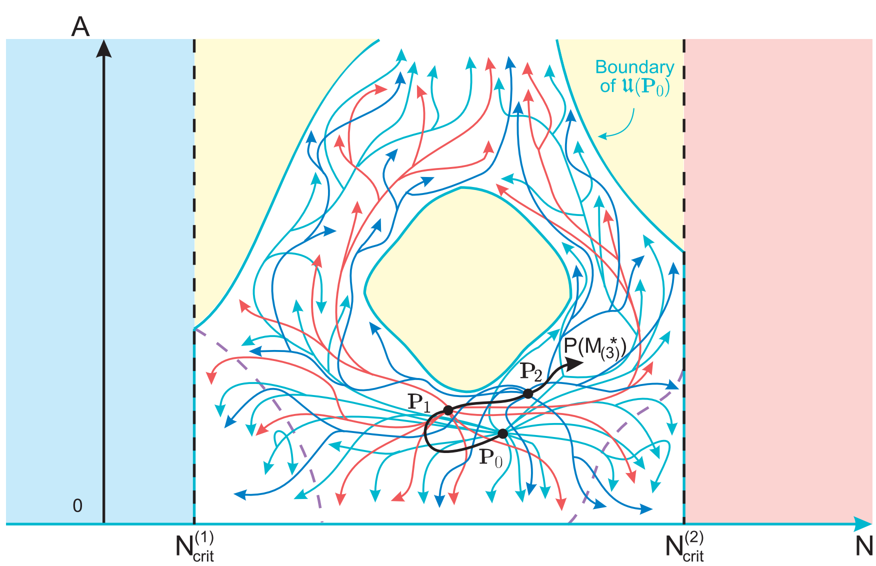

Fig. 6. Sketch of weak Brundtland management in our two-dimensional toy world. $\mathbf{M}^*_{(3)}$ generates a coevolution path $\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})$ that preserves the asymptotic E & D options. For example, all states in $\mathfrak{U}(\mathbf{P}_0)$ can ultimately be reached from $\mathbf{P}_1 \equiv \mathbf{P}(\hat{t}_1 \mid \mathbf{M}^*_{(3)})$ and $\mathbf{P}_2 \equiv \mathbf{P}(\hat{t}_2 \mid \mathbf{M}^*_{(3)})$, respectively

as "anti-Murphy schemes for SD". We confine ourselves here to a single illustrative example, called "weak anti-Murphy strategy".

This particular operationalization of the precautionary principle rests on the conviction that a future aberration of coevolution into some catastrophe domain cannot be ruled out completely for socio-economic and scientific reasons. Yet the degree of long-term disaster risk can be limited to an acceptable level. The basic idea is to admit only those control sequences $\mathbf{M} \in \mathfrak{M}$ generating coevolutionary paths from which catastrophe domains might be approached later on by rather drastic mismanagement only. Thus the weak anti-Murphy scheme tries to suppress conceivable – and perhaps fatal – errors of coming generations well in advance. The scheme can be made specific by introducing the x-risk environment of a given catastrophe domain $\mathfrak{K}$, symbolized by $\mathfrak{R}_x(\mathfrak{K})$. This set is defined to embrace all those points in coevolution space which are connected to $\mathfrak{K}$ by a fraction $y \geq x$ of all possible management sequences contained in $\mathfrak{M}$. The complement of $\mathfrak{R}_x(\mathfrak{K})$ in $\mathfrak{U}(\mathbf{P}_0)$ may be called the *x-safety zone with respect to* $\mathfrak{K}$ and symbolized by $\mathfrak{S}_x(\mathfrak{K})$. Now the geocybernetic task associated with this variant of $\mathcal{P}_2$ can be formulated as follows: Given some risk standard $\hat{x} \in [0, 1]$, determine and employ a management sequence $\mathbf{M}_{(2|\hat{x})} \in \mathfrak{M}$ such that the coevolution path $\mathbf{P}(t|\mathbf{M}_{(2|\hat{x})})$ develops entirely within the x-safety zone $\mathfrak{S}_{\hat{x}}(\mathfrak{K})$. As a matter of fact, a general mathematical theorem can be proven that the set $\{\mathbf{M}_{(2|\hat{x})}\}$ of "weak anti-Murphy managements" is not void if certain (mild) conditions are satisfied. Figure 5 visualizes the formal analysis just sketched in our tutorial "earth system" for a safety standard $\hat{x} = 0.5$. We leave the pessimization paradigm with the remark that catastrophe domains can be well-defined entities as derived from ecosphere modelling, for instance. A rather bewildering example has been recently given by Stocker and Schmittner (1997) who identify the overall CO_2 emissions regime jeopardizing the stability of the thermohaline oceanic circulation.

Equitization

Most of the E & D debate with its preliminary climax in Rio in 1992, revolves around notions such as "fairness", "justice" and, in particular, "intergenerational equity". If we identify the latter term with "equality of E & D options for successive generations", we are able to formulate a crisp SD paradigm, $\mathcal{P}_3$ in Table 1, which can replace the evasive Brundtland definition of SD (see E1). There are, again, several distinct ways to operationalize this paradigm, and we pick only one in order to illustrate what equitization is all about, namely the *"weak Brundtland strategy"*.

The basic idea behind this scheme is quite simple: Let $\hat{\mathbf{P}} = \mathbf{P}(\hat{t} \mid \hat{\mathbf{M}})$, i.e. $\hat{\mathbf{P}}$ is the specific coevolution state created at the time $\hat{t}$ by steering the $\mathcal{N}-\mathcal{A}$ complex from its point of departure, $\mathbf{P}_0$, with the control element $\hat{\mathbf{M}}$. Due to causality, we clearly have:

$$\mathfrak{U}(\hat{\mathbf{P}}) \subset \mathfrak{U}(\mathbf{P}_0) \tag{4}$$

where $\mathfrak{U}(\hat{\mathbf{P}})$ denotes the "accessible universe" with respect to the new starting point $\hat{\mathbf{P}}$. If $\mathfrak{U}(\hat{\mathbf{P}})$ is a true sub-set of $\mathfrak{U}(\mathbf{P}_0)$, then certain states might not be attainable from $\hat{\mathbf{P}}$ any more although they were from $\mathbf{P}_0$; thus E & D options are lost down the coevolutionary line. Such an impairment of "self-determination rights" of future generations can be avoided, in principle, by the right choice of the management sequence from the pool $\mathfrak{M}$. The weak Brundtland operationalization of $\mathcal{P}_3$ actually aims at guaranteeing inter-generational equity of options in at least an *asymptotic sense*, i.e. for an infinite planning horizon. The formal prescription reads as follows:

Determine a control element $\mathbf{M}^*_{(3)}$ such that for arbitrary $\hat{t} \geq 0$ the relation:

$$\mathfrak{U}(\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)})) = \mathfrak{U}(\mathbf{P}_0) \tag{5}$$

holds. In other words, the respective accessible universes $\mathfrak{U}(\mathbf{P}(\hat{t} \mid \mathbf{M}^*_{(3)}))$ do not shrink as time goes by. This situation is depicted in Fig. 6. Much more subtle operationalizations of the equitization paradigm may be devised. For the sake of brevity, we will not elaborate on this point here and instead conclude this entire section with a comment on the *composition* of "pure SD paradigms": for most practical purposes of geocybernetics "complex paradigms", which blend the principles of the distinct $\mathcal{P}_n$'s (as classified in Table 1) in the spirit of *multi-objective decision-making* (e.g. Bell et al. 1977), will provide superior guidelines compatible with the real preferences of the global society.

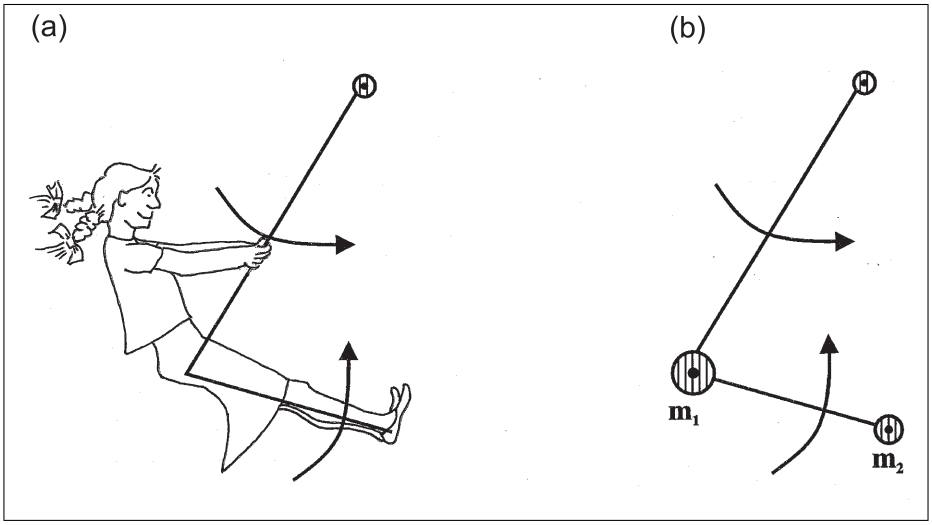

Fig. 7. The double pendulum subject to a homogeneous gravitational field (b) represents a physical caricature of the swinging girl (a)

Fuzzy Control: Why Geocybernetics Is Feasible

In spite of the breathtaking progress that ecosphere (and even anthroposphere) analysis has been making over the past few decades (see above), the remaining ocean of ignorance seems infinite. At least we are starting to learn how to chart this ocean and to tell non-intelligible from intelligible, i.e. to single out those items we will never be able to understand, let alone foresee. Our ignorance with respect to geocybernetic issues may be classified according to the following taxonomy. We must face:

- *Removable cognitive uncertainty*, i.e. the scientific domain where intensive research may finally generate precise information on the composition, processes and conditions of the systems involved.
- *Irremediable cognitive uncertainty*, i.e. all the aspects of the subject in question, which are rigorously determined, in principle, by the laws of nature yet cannot be specified crisply at a given point in time (this type of uncertainty is especially characteristic of highly heterogeneous nonlinear systems).
- *Voluntative uncertainty*, i.e. the fundamental indeterminacy of future E & D dynamics due to the "freedom of will" of the billions of actors (individuals, companies, nation states, etc.) cooperating or competing in the global game.

So, do we really have the courage and, more importantly, a chance to start controlling the utterly complex earth system? This question about the feasibility of geocybernetics clearly must precede the third key question formulated above, which must be answered in a political process (in the widest sense of the term) anyway. Salvation will probably not come from "geoengineering", i.e., tinkering with the ecosphere in the well-known end-of-the-pipe fashion employed to alleviate local environmental problems like oil spills or toxic waste. Thus the stimulation of the marine "carbon pump" by iron-fattening of the plankton carpets in the tropical seas (E3) in order to compensate anthropogenic CO_2 emissions, for instance, is bound to fail the target due to cascades of scale and side effects.

We will have to find a more sophisticated way towards global E & D management, an avenue actually indicated by the girl operating a garden swing (E2). The girl-swing system is in fact a considerably complicated version of the mathematical double pendulum (see Fig. 7). The latter dynamic system is quite famous for exhibiting deterministic chaos of the finest quality that renders the motion virtually unpredictable. Yet, without having the foggiest idea of Hamiltonian mechanics culminating in the celebrated KAM theorem (Arnold 1978), our child is capable of controlling the swing in order to generate a regular motion of any desired amplitude! Let us give another example *how seemingly unfeasible control problems are perpetually solved by ordinary people in everyday life*. Imagine a tourist who wishes to cross the overcrowded Piazza San Marco (Venice) in a certain direction on a sunny August afternoon. This constitutes a manoeuvring task that could not be mastered by any conceivable initial instruction of the tourist in the sense of a locomotive ("ballistic") programme. Due to the cognitive and voluntative un-

Table. 2. Comparison of four basic root-finding scenarios for the test function $g(x)$ and the common point of departure $x_0 = 0.2$. (x_n the n-th approximation to the target within the framework of the respective algorithm)

	Newton's Method		Perturbation Method	
	Deterministic	Noisy	Deterministic	Noisy
n	x_n	x_n	x_n	x_n
0	0.2	0.2	0.2	0.2
1	0.4476033 10^{-1}	0.5162266 10^{-1}	0.4476033 10^{-1}	0.4671267 10^{-1}
2	0.2061910 10^{-2}	0.4757890 10^{-2}	0.8406512 10^{-2}	0.1126749 10^{-1}
3	0.4257312 10^{-5}	0.9068513 10^{-5}	0.1140281 10^{-2}	0.4271971 10^{-2}
4	0.1812476 10^{-10}	0.6112070 10^{-6}	0.2275428 10^{-4}	0.3209610 10^{-2}
5	-0.5382865 10^{-21}	0.2854914 10^{-7}	-0.5181396 10^{-4}	0.3139614 10^{-2}
6	-0.1079167 10^{-42}	0.8589053 10^{-9}	-0.2210679 10^{-4}	0.3167149 10^{-2}
7		0.4926537 10^{-10}	-0.5976345 10^{-5}	0.3181912 10^{-2}
8		0.1745666 10^{-11}	-0.1124674 10^{-5}	

certainties involved, our single-minded sleep-walker would run into other tourists in no time at all. But real tourists do manage traversing the Piazza again and again, and they even succeed in keeping to the preselected direction by sporadic re-orientation with the help of a prominent landmark like the red-brick Campanile.

The secret behind these accomplishments humiliating the scientific community is "fuzzy control". Its recipe for surviving the daily rat-race of muddling through intricate situations reads as follows:

Based on uncertain and/or fragmentary information, adopt a rough long-term and/or large-scale strategy, which must be continuously readjusted in an approximate fashion according to all sorts of generally imprecise additional data.

The slowly evolving scientific justification for this recipe is mainly based on Zadeh's pioneering work (Zadeh 1973; see also more recent work like Kandel and Langholz 1993) and identifies three major systemic prerequisites, namely,

- The existence of *leeway*, i.e. the option of deviating at least moderately from an ideal course without immediately missing the target or even wreaking havoc.
- A moderate *responsiveness* as defined by the respective velocities of system variability, information updating and measure implementation.
- A rough *panoramic view* warranting global spatiotemporal orientation in order to avoid dead-end streets and points of no return.

Returning to our geocybernetic challenge, we claim that judicious combination of the smart control methods transpiring from modern complex systems theory (see above), together with the "fuzzy recipe" formulated in this section will be capable of doing the job. This boils down to trying to shape the global E & D process in spite of the insight that the future of the earth system cannot be predicted ! However, the geocybernetic dream can only come true if the general prerequisites listed above are operationalized in the context of global E & D management in the following ways:

- Observance of the *precautionary principle*, i.e. staying away from presumed civilizatory and ecological load limits ("leeway").
- Creation and cultivation of *flexible instruments*, i.e. international decision mechanisms, institutions and infrastructures that allow for perpetual readjustment ("responsiveness").
- Incessant exploration of virtual coevolution futures in computer-animated model earth systems ("panoramic view").

As an illustration of the potential power of fuzzy control, we put forward the fact that one of the most efficient algorithms of numerical mathematics, namely *Newton's root-finding method*, actually realises iterative control resistant against (moderate) uncertainty. The trick that makes this method so successful consists in the *continuous readjustment of the approximation basis*, i.e. the first approximation to the desired root is the starting point for the second approximation, and so on. This sounds almost trivial, yet markedly differs from the strategies employed in conventional perturbation theory (Berry 1978). The superiority of Newton's method is demonstrated in

Table 2 for the simple task of finding the root $\hat{x} = 0$ of the function:

$$g(x) = \tan(\frac{\pi}{4} + x) - 1 \tag{6}$$

The efficiency of the Newtonian scheme remains unshattered even when the information on the function g and its derivatives is distorted by noise from a random-number generator during the approximation process. Newton's "noisy" method is in fact a clear-cut formal paradigm for fuzzy control.

Outlook: Where Geocybernetics May Be Heading

The Third Conference of the Parties to the UN Framework Convention on Climate Change took place in December 1997 in Kyoto, Japan. When we look back on this event in 20 or 30 years from now, we will realize that the Kyoto protocol (specified in a preliminary, innocent-looking document referred to as FCCC/CP/1997/L.7/Add. 1) marked a *historic turning point* ushering in the geocybernetic age: for the first time ever the international community has decided to exercise concerted control of a global-scale issue in spite of the fact that this control may affect the short-term interests of billions of people on this planet in a negative way ! And those who are able to uncover the iridescent climate-protection logics underlying the protocol, or who have even witnessed the chaotic making of this document, will not hesitate to certify the "fuzziness" of this E & D measure. But a step in the right direction, namely net reduction of greenhouse-gas emissions from the industrialized countries, has been made, and the climate system is benevolent enough to allow for midway corrections on the road to 2012 and beyond.

Note that the fuzzy control principle of in-built perpetual imprecise revision has already been implicitly adopted for the "Montreal Protocol on Substances that Deplete the Ozone Layer" (http://www.unep.ch/ozone/montreal.htm; see especially Articles 6, 2.9 and 2.10). In comparison with the climate protection task, however, stratospheric ozone management is truly child's play.

We are currently learning geocybernetics by doing it. Once ecosphere modelling and its other major prerequisites have come of age, a number of *sophisticated options for global E & D management* will be available. In particular, subtle ways of climate engineering may become feasible that suppress, e.g., the abrupt cooling episodes which have afflicted our planet in a rhythm of roughly 1500 years even during the Holocene. And what about mitigating or even preventing potential ice ages arising from eternal astrophysical mechanisms ? Some people already argue today that a considerable fraction of the global reserves of fossil fuels should be set aside until the time when their burning could deliberately amplify the natural greenhouse effect in order to counteract the sagging of solar irradiation. This would be an extremely clumsy method of climate stabilization, however, which could be refined at least by injecting into the atmosphere, instead of CO_2, tiny amounts of powerful "designer gases" tailored to fine-tuning of earth's radiation balance. However, on the basis of a considerably advanced understanding of the ecosphere's metabolism, much smarter schemes will transpire from the geocybernetic debate. One could imagine, for example, that specific modifications of the terrestrial vegetation cover would "desensitize" the planet against glaciation by thwarting runaway insolation-albedo-growth effects.

It is conceivable, on the other hand, that geocybernetics will follow completely different (or complementary) courses that lie more in the realm of social management. Here the demographic issue overrides other themes: Is there an optimal number of human beings to be supported by the ecosphere ? What is the right mix of condensing people in cities and dispersing them across landscapes ? and so on. If answers to these questions are available at all, then any attempt to implement that wisdom will have to be conducted with the utmost delicacy and sense of responsibility.

We conclude this article by pointing out that geocybernetics will not become a real success story if the present mismatch between the spatiotemporal scales of E & D interference as opposed to E & D control is not removed soon. While the borders of nation states have become almost irrelevant to global economic players (for instance) after the end of the Cold War, human and natural rights are still confined and dominated by thousands of frontiers. This situation can only be overcome by giving up a good deal of national sovereignty and establishing a true regime of *global governance*. As a prerequisite, the rather symbolic parts and pieces of the UN system must be transformed into powerful supra-national institutions: *allons corriger le futur* !

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