‘Earth system’ analysis and the second Copernican revolution

H. J. Schellnhuber

Optical magnification instruments once brought about the Copernican revolution that put the Earth in its correct astrophysical context. Sophisticated information-compression techniques including simulation modelling are now ushering in a second ‘Copernican’ revolution. The latter strives to understand the ‘Earth system’ as a whole and to develop, on this cognitive basis, concepts for global environmental management.

There are many ways of looking forward in time. One of the most amusing (and sometimes terrifying) is the ‘forward-view mirror’ — contemplation of the future by reflecting on the past. If we consider the unravelling of the mysteries of the human body by physicians over the past three millennia, we see much that is relevant to unravelling the mysteries of the Earth’s physique, or “Gaia’s body”[1].

With our present-day understanding of medical science, it seems incredible that the Hippocratic school, which based analysis and prognostics of the human body on the ‘composition of the humours’ of individual patients, dominated Western medicine well beyond the Renaissance. Great leaps in knowledge, such as Vesalius’s anatomical revelations published in 1542, or Harvey’s physiological studies in 1628, were ignored or suppressed — notably by the deans of Paris’s ‘infallible’ medical faculty. The first scientific treatise relating contagious diseases to activities of microorganisms, rather than harmful vapours, or ‘miasmas’, did not appear until 1840[2].

When the Enlightenment came, its ultimate triumph was based, literally, on light — the ability to process radiation received from objects of specific interest. The invention of the operational microscope in 1608 by the Dutch spectacle-maker Zacharias Jansen, realizing a proposal made in 1267 by Roger Bacon, was a turning-point in scientific history. For the first time the human eye could transcend its natural limits and begin to explore the wonders of the microcosmos.

Many more wonders awaited revelation through the processing of light — above all, the spangled nocturnal heavens with their billions of gigantic entities made so tiny by distance. Once again, faint rays of light emitted by objects had to be invigorated through ingenious devices, in this case telescopes. And so optical amplification techniques brought about the great Copernican revolution, which finally put the Earth in its correct astrophysical context.

Today, some 500 years after Copernicus, Cusanus and company, our civilization sets about visiting neighbouring planets, scrutinizing stellar objects at the brink of creation, and even tracking down extraterrestrial

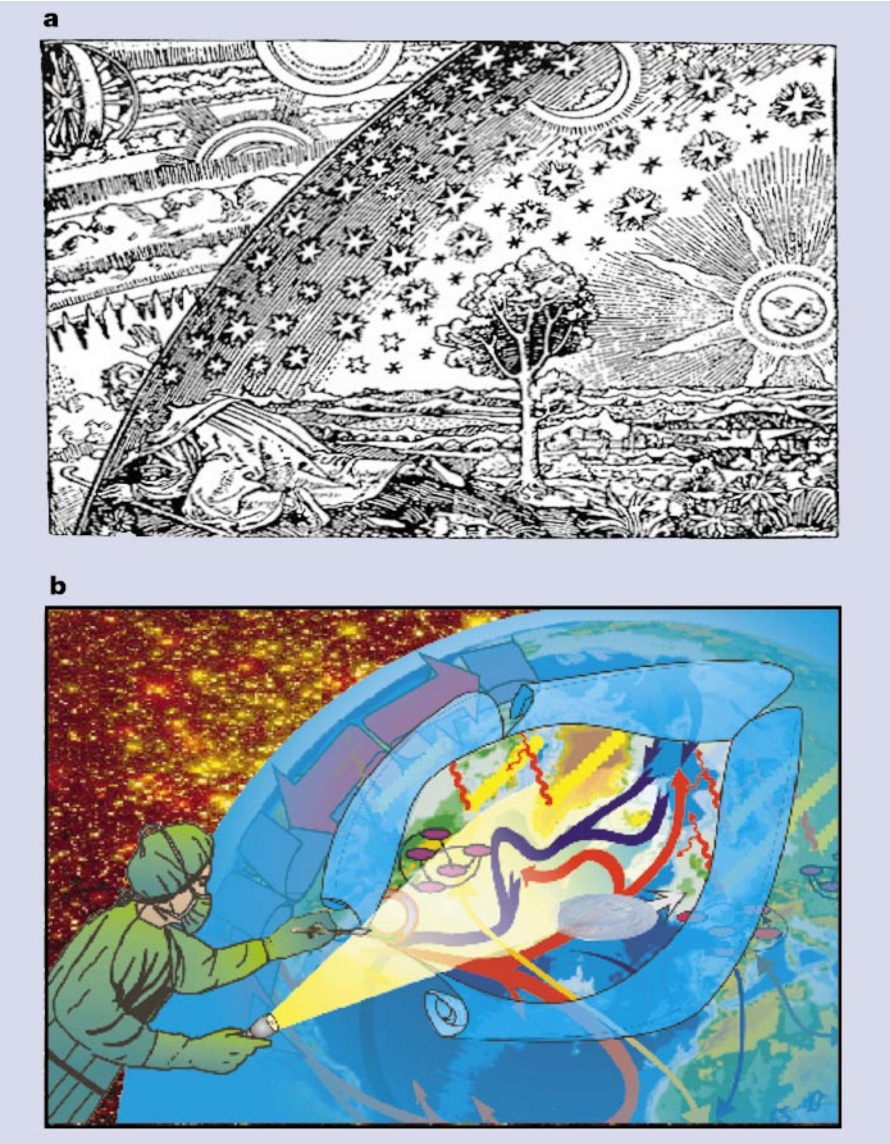

Figure 1 **A tale of two revolutions.** a, **The shock of the Enlightenment as expressed in a (probably apocryphal[26]) fifteenth-century woodcut.** b, **‘Earth-system’ diagnostics in the twenty-first century.**

intelligence. This spectacular augmentation of the Renaissance impulse is being accompanied by a crescendo of other scientific activities which will soon culminate in a second 'Copernican' revolution. This new revolution will be in a way a reversal of the first: it will enable us to look back on our planet to perceive one single, complex, dissipative, dynamic entity, far from thermodynamic equilibrium — the 'Earth system'. It may well be nature's sole successful attempt at building a robust geosphere–biosphere complex (the ecosphere) in our Galaxy, topped by a life-form that is appropriately tailored for explaining the existence of that complex, and of itself.

Such an explanation needs eventually to encompass all the pertinent processes linking the system's constituents at all scales — from convection deep in the Earth's mantle to fluctuations at the outer limit of the atmosphere. New instruments are necessary, especially macroscopes[3] which reduce, rather than magnify as microscopes do, giving Earth-system scientists an objective distance from their specimens — no longer too close for cognitive comfort.

There are three distinct ways to achieve 'holistic' perceptions of the planetary inventory, including human civilization:

1. The 'bird's-eye' principle.
An obvious trick for obtaining a panoramic view of the Earth is to leave it, and observe it from a distance. The race to the Moon in the 1960s opened up the opportunities for this particular macroscope technique, and created the now-familiar image of our blue planet floating in the middle of a dark, cold nowhere. The trick was not exactly cheap, however; NASA's lunar ventures absorbed some US$95 billion overall. Now, space stations, shuttles and an armada of smart satellites are about to establish the details of a complete Earth reconnaissance.

2. The digital-mimicry principle.
A more sophisticated, and less expensive, macroscope technique is simulation modelling. Here, components and processes of the original Earth system are replaced by mathematical representatives as accurate as our evolving knowledge allows. These formal chimaeras are then animated electronically, to imitate the dynamic complex of real relationships, in virtual space-time. The menagerie of Earth-system models includes tutorial, conceptual and 'analogical' specimens[4]. One significant advantage of this macroscope is that it allows a multitude of potential planetary futures to be played out, with no more a risk than a computer crash. The validation of Earth-simulation machines remains problematic, although relentless training with palaeorecords can teach them satisfactory hind-casting skills (see, for example, refs 5–7).

3. The 'Lilliput' principle.
As a third option, there is the 'incredible shrinking Earth' idea, as enacted in the Sonora Desert in Biosphere II (ref. 8). The idea involves rebuilding the ecosphere in flesh, blood and rock, on a scale reduced by many orders of magnitude. Such a nano-planet can be conveniently scrutinized for operational stability or emerging self-organization processes. Despite its disastrous performance, the Biosphere-II project provoked fresh scientific attitudes towards life. And in fact, the free-air experiments[9], which are currently being used to investigate the effect of atmospheric CO_2 enrichment on agroecosystems and forests, subscribe to a similar empiricist philosophy.

Most probably, the future of macroscopes will be dominated by intelligent combinations of these principles, particularly the first two. Planetary monitoring — by remote sensing and a worldwide net of *in situ* measurement devices — will be complemented and synchronized by data models to generate a continuously updated digital 'Weltbild'.

The quasi-antithetical spirits of the first and second Copernican revolutions may be visualized by contrasting a famous ancient allegory with a modern cartoon (Fig. 1). The explorer featured in Fig. 1b is dressed as a doctor for two reasons. First, the continuing investigation into the Earth's physique is in many respects reminiscent of the exploration of the human body during the Renaissance. Science historians looking back from, say, AD 2300, will tell yet again a tale of incredible delusions and triumphs. And second, a significant impetus behind the second Copernican revolution is the insight that the ecosphere's operation may be being transformed qualitatively by human interference. So the macroscope is a diagnostic instrument, generating evidence necessary for treatment[10].

This means that we are confronted ultimately with a control problem, a geo-cybernetic task that can be summed up in three fundamental questions[11]. First, what kind of world do we have? Second, what kind of world do we want? Third, what must we do to get there?

These questions indicate the immensity of the challenge posed by Earth-system analysis[12]. I would like now to narrow our gaze to a few crucial aspects of this transdisciplinary adventure, using the light of the latest progress in pertinent science, particularly that orchestrated by the International Geosphere–Biosphere Programme (IGBP; see Box 1)[13].

Box 1 The International Geosphere–Biosphere Programme (IGBP)

Each day seems to bring new discoveries — of mega-fluctuations, long-distance teleconnections, feedback loops or phase-transition lines in the entrails of the planetary ecosystem. This development is driven predominantly by IGBP research and is shedding new light on past, present and future global changes. For example, one IGBP core project involves reconstructing, in great detail, global and regional climatic history as far back as 500,000 years ago[27]. Another major project is more concerned with the current operational mode of the Earth system. It tries to solve the 'puzzle' of oceanic CO_2 flux in a geographically explicit way. Intermediate results indicate that CO_2 is upwelling and leaving the ocean in the subarctic western Pacific Ocean in winter, in the Persian Gulf in summer, and west of South America all year round. In contrast, oceanic regions, where warm currents like the Gulf Stream and the Kuroshio are being cooled, take up large amounts of CO_2 (ref. 28).

Complementary activities scrutinize the CO_2 metabolism of the terrestrial biosphere. Recent findings provide hints that the continental ecosystems may turn into a carbon source as a result of climate change at some time in the next century. A subtle combination of factors, including changes in fire, storms and pest infestations, is responsible for this discomforting prospect[29]. Another disturbing result was obtained in the coastal zone: model-supported forecasting of the geochemical effects on coral reefs of anthropogenic CO_2 build-up in the atmosphere demonstrates the high vulnerability of these ecosystems. Crucial mechanisms for reef accumulation in the tropics could be weakened by 30 per cent by 2050[30].

Understanding the Earth system

At the highest level of abstraction, the make-up of the Earth system $\boldsymbol{E}$ can be represented by the following 'equation':

$$\boldsymbol{E} = (\boldsymbol{N}, \boldsymbol{H}) \qquad (1)$$

where $\boldsymbol{N} = (\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \ldots)$; $\boldsymbol{H} = (\boldsymbol{A}, \boldsymbol{S})$.

This formula expresses the elementary insight that the overall system contains two main components, namely the ecosphere $\boldsymbol{N}$ and the human factor $\boldsymbol{H}$. $\boldsymbol{N}$ consists of an alphabet of intricately linked planetary sub-spheres $\boldsymbol{a}$ (atmosphere), $\boldsymbol{b}$ (biosphere), $\boldsymbol{c}$ (cryosphere; that is, all the frozen water of Earth), and so on. The human factor is even more subtle: $\boldsymbol{H}$ embraces the 'physical' sub-component $\boldsymbol{A}$ ('anthroposphere' as the aggregate of all individual human lives, actions and products) and the 'metaphysical' sub-component $\boldsymbol{S}$ reflecting the emergence of a 'global subject'. This subject manifests itself, for instance, by

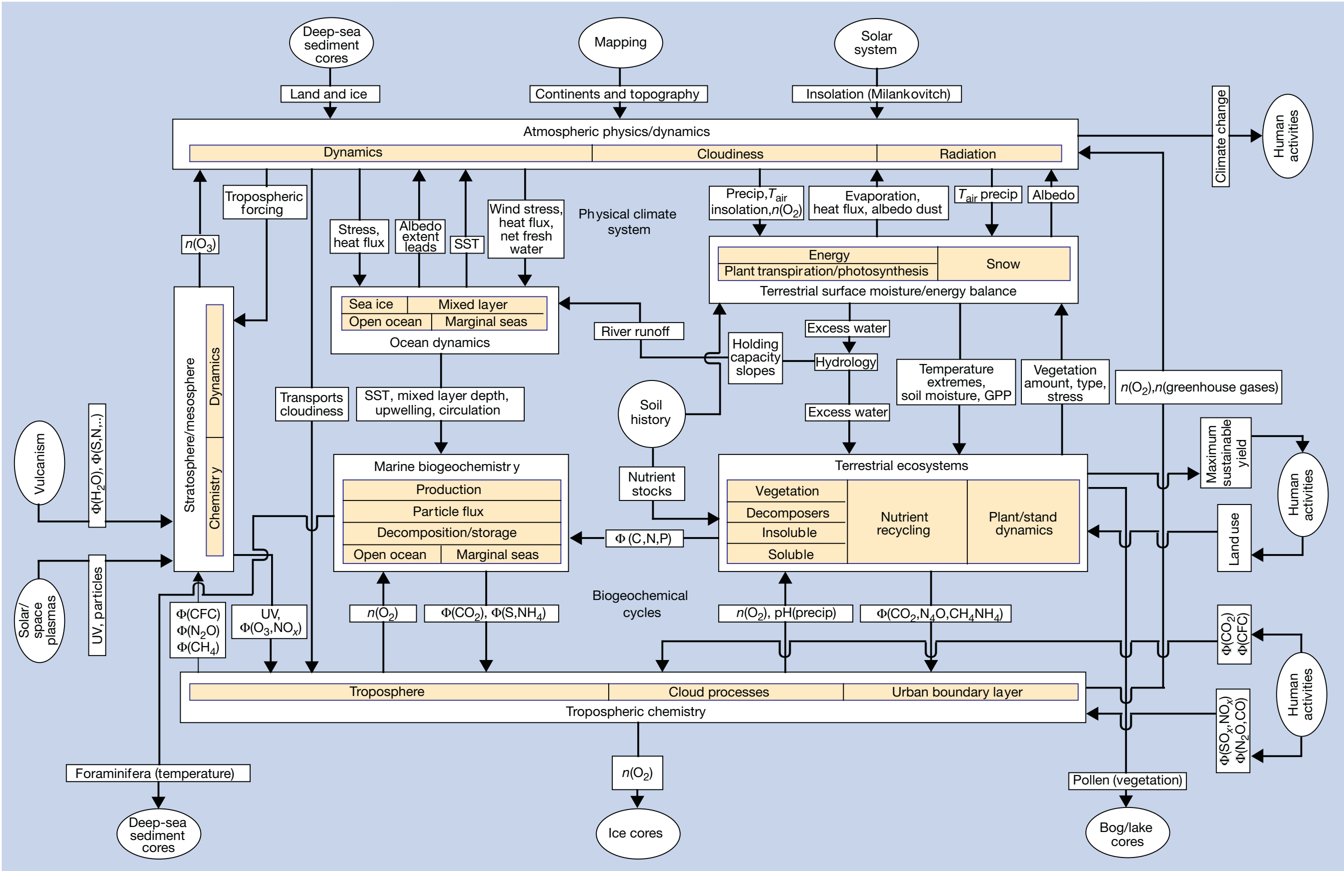

Figure 2 **A simplistic conceptual model of the planetary machinery (reconstructed on the basis of ref. 14).**

adopting international protocols for climate protection.

For the time being, I will not try to provide additional justification for my decomposition of ***E***, but rather focus on its material physique, that is, the pair (***N***, ***A***). A useful, although highly simplistic, way of representing this global entity is the famous Bretherton diagram[14] as depicted in Fig. 2. This 'wiring diagram' arose out of a brainstorming exercise conducted by eminent geosphere–biosphere scholars back in 1985.

Although the Bretherton caricature of ***N*** (***A*** is compressed here into a few 'black boxes') is obviously impromptu, static and partly inconsistent, it has since been the subject of attempts at further simplification, not sophistication. This is surprising considering the firework display of scientific findings about the ecosphere illuminating the last decade of this century. Any recent issue of the popular UK science magazine *New Scientist* gives an indication of the excitement. Take the issue of 3 July 1999, for example: on page 17 there is speculation over the relationship between global warming and the rotation velocity of the Earth; on page 22 the synergies between the North Atlantic Oscillation, Sahelian droughts and coral-reef die-back are tentatively identified; on page 25 it is argued that comet particles are responsible for a "mysterious layer of water vapour that hangs 70 kilometres above the tropics"; and on page 49 there is a discussion of the impact of starfish population dynamics on the rise in atmospheric CO_2. Veils of ignorance are being lifted wherever we look, and much of this information is the result of research supported by the IGBP.

Ecosphere science is therefore coming of age, lending respectability to its romantic companion, Gaia theory, as pioneered by Lovelock and Margulis[15]. This hotly debated 'geophysiological' approach to Earth-system analysis argues that the biosphere contributes in an almost cognizant way to self-regulating feedback mechanisms that have kept the Earth's surface environment stable and habitable for life.

Taken to an extreme, the Gaia approach may even include the influence of biospheric activities on the Earth's plate-tectonic processes — through modulation of thermal and viscous gradient fields across the upper geological layers. The inverse is already backed up by science: plate tectonics is a powerful regulator of biosphere-subsistence conditions. It recycles the fundamental nutrient, carbon, between atmosphere and ocean floor over some 500,000 years. It can also be demonstrated, taking further the ideas of Caldeira, Kasting and others, that this 'carbonate–silicate loop' will support the well-being of photosynthetic life on Earth for another 500 to 700 million years — but no longer[16].

But is it really Gaia who commands the engine room of the Earth system? Palaeorecords do not provide a clear answer to this question. What we do know is that rather small and regular external perturbations, like faltering insolation, repeatedly provoked the ecosphere into alternative modes of operation; glaciations in the Quaternary period seem to be a conspicuous example of such a self-amplifying response, although the precise mechanisms at work are not yet fully understood (see, for example, ref. 17).

The giant strides of biospheric evolution, on the other hand, were probably enforced by true catastrophes such as asteroid impacts, mass eruptions of volcanoes and cosmic-dust clouds passing across the Solar System. Disasters like these will continue to shake our planet quite frequently; for example, impact events releasing energy equivalent to 10 gigatons of TNT are estimated to recur on average every 70,000 years[18].

Although effects such as the glaciations may still be interpreted as over-reactions to small disturbances — a kind of cathartic geophysiological fever — the main events, resulting in accelerated maturation by shock

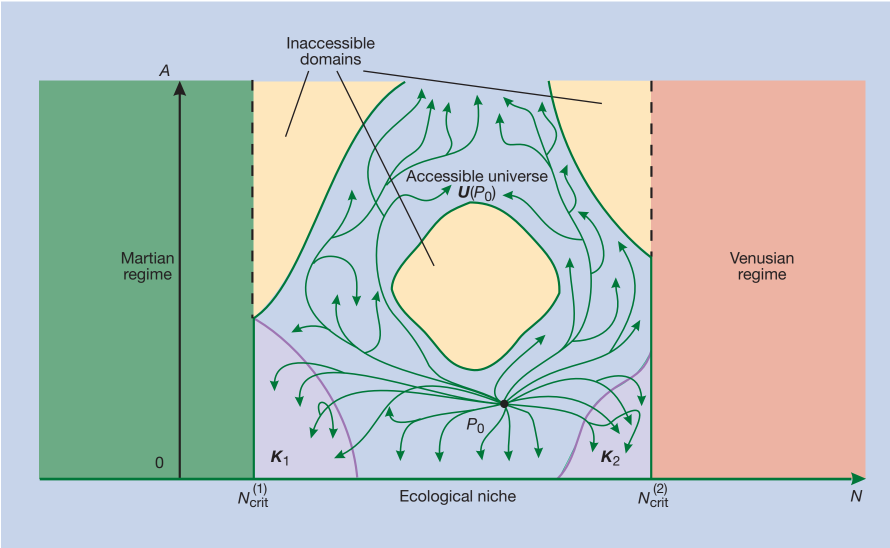

Figure 3 **A 'theatre world' for representing paradigms of sustainable development. The space of all conceivable co-evolution states $P = (N, A)$ is spanned by a 'natural' axis, N (representing, say, global mean temperature) and a civilizatory axis, A (representing, say, global gross product). Vertical lines at $N_{crit}^{(1)}$ and $N_{crit}^{(2)}$ delimit the niche of subsistence states for humanity between an ultra-cold 'Martian regime' and an ultra-hot 'Venusian regime'. The domain $U(P_0)$ ('accessible universe') embraces all possible co-evolution states that can be reached from the present state P_0 by some management sequence from the overall pool. $U(P_0)$ contains specific 'catastrophe domains' K_1 and K_2.**

treatment, indicate that Gaia faces a powerful antagonist. Rampino has proposed personifying this opposition as Shiva, the Hindu god of destruction[19].

About four billion years into Earth's history, a third planetary might emerged, a challenger to these two intransigent forces: human civilization. Let us stay with mythological imagery and call this power Prometheus. For the purposes of Earth-system analysis, Prometheus is to be identified with the mega-factor $\boldsymbol{H}$ in equation (1).

There is no need to reel off a tally of environmental folklore about the influence of Prometheus on the ecosphere: the ozone lesson is enough to show that humanity is indeed capable of modifying $\boldsymbol{N}$ at a strategic level. There is overwhelming evidence that the stratospheric ozone shield against harmful UV-B radiation has been perforated accidentally by industrial by-products, in particular by chlorofluorocarbons (CFCs). The physicochemical processes causing this disturbing effect are intricate; they were deciphered only a few years ago and the elucidators awarded a Nobel prize. But "things could be much worse", as one of the laureates, Paul Crutzen, puts it: "Bromine is almost a hundred times more dangerous for ozone than chlorine. If the chemical industry had developed organobromine compounds instead of CFCs then...we would have been faced with a catastrophic ozone hole everywhere and all year-round during the 1970s — probably before atmospheric scientists had developed the knowledge necessary to identify the problem."[20]

We have been extremely lucky in being granted the chance of correcting our ways through the Montreal ozone-protection protocol. Ironically, the eminent meteorologist Chapman suggested back in 1934 creating artificial ozone holes by injecting appropriate ozone depletors into the stratosphere as a way of improving astronomy's ultraviolet remote-sensing accuracy[21].

Global environmental change is all around us now, and the material components of the Earth system, $\boldsymbol{N}$ and $\boldsymbol{A}$, are behaving like a strongly coupled complex. To assess the crucial consequences of this phase transition in planetary history, we must, and can, do better than drawing wiring diagrams of the Bretherton type. Quite recently, IGBP launched a promising macroscope-making initiative aimed at advancing Earth-system models of intermediate complexity (EMICs; see Box 2). These models seek to integrate the main processes and forces — Gaia, Shiva and Prometheus — through effective quantitative equations. Ideally, they would simulate all of the pertinent features of the $\boldsymbol{N}$–$\boldsymbol{A}$ complex on the system's level, and operate fast enough to serve as 'time machines' — producing virtual vistas of the far environmental past and future[6,7].

It has become clear, however, that our quantitative mimicry skills for anthroposphere processes (like industrial growth or transmigration dynamics) lag far behind our ecosphere-simulation capacity. The most capable sub-models currently available for representing relevant socioeconomic components of the Earth system are those used in 'integrated assessments of climate change'[22]. But these instruments are still far too crude — a problem scientific progress must soon remedy. Massive intellectual and financial investments should generate adequate (long-term, non-equilibrium, multi-actor) modules within the next two decades.

Controlling the Earth system

Now assume that the research community does its job and develops a perfect hierarchy of transdisciplinary EMICs. Who will use the insights, the hindsights and foresights generated by these time machines? And in what way? These questions prompt us to revisit the human factor $\boldsymbol{H}$ in the Earth-system equation (1). Formally, $\boldsymbol{H} = (\boldsymbol{A}, \boldsymbol{S})$, where $\boldsymbol{A}$ reflects the physiological–metabolic contribution of global civilization to planetary operation. This contribution is qualitatively not dissimilar to the role played by the sheep of the world, which reflect sunlight (albedo effect), overgraze pastures (soil degradation) and emit the powerful greenhouse gas methane.

But $\boldsymbol{H}$ embraces a second sub-factor, $\boldsymbol{S}$, which makes all the difference. This entity, introduced as the 'global subject' above, represents the collective action of humanity as a self-conscious control force that has conquered our planet. The global subject is real, although immaterial. One key to its emergence from the physical basis is worldwide communication. As you read this essay, you are engaging in an indirect dialogue with the author. That is insignificant, however, compared with the direct global 'polylogue' taking place via the Internet. Global telecommunication will ultimately establish a cooperative system generating values, preferences and decisions as crucial commonalities of humanity online.

The building and application of macroscopes will be of tremendous help to the global subject in finding its identity. An ever-evolving Earth-observation system[23] will allow $\boldsymbol{S}$ to watch its own footprints on the ecosphere, and Earth-simulation models will enable $\boldsymbol{S}$ to make collective 'rational choices' on the system's level. Finally, densely linked global institutions, as well as innumerable worldwide activists' networks, will help enforce resolutions of $\boldsymbol{S}$, such as those made in international environmental conventions. This is the emergence of a modern 'Leviathan', embodying teledemocracy[3] and putting the seventeenth-century imagination of the English philosopher Thomas Hobbes into the shade.

The global subject will reign over the centuries to come. One of its most responsible tasks will be to seek out a tolerable environmental future from the infinity of optional co-evolutions of $\boldsymbol{N}$ and $\boldsymbol{A}$. In other words, $\boldsymbol{S}$ must guarantee sustainable development. In spite of, or because of, its fuzziness, the notion of sustainable

Box 2 Intermediate-Complexity Modelling

When devising Earth-system models, scientists have to resist two fatal attractions. The first one is over-simplification, which tends to ignore even crucial elements of planetary dynamics like the episodic warming of tropical East Pacific ('El Niño'; see Ref. 31). The second one is over-sophistication, often resulting in bulky and horrendously expensive models that defy a transparent analysis no less than the reality to be simulated. A compromise strategy tries to retain just the right degree of complexity by averaging over the details irrelevant to the issue studied. This can be achieved by constructing reduced-form representations of the full set of dynamic equations according to well-known principles from scientific computing. As far as the atmosphere module is concerned there exists, for instance, the option to separate 'slow' and 'fast'variables[32] or to apply filtering techniques to the primitive equations of motion[33].

development has become an end-of-millennium *idée fixe*. Entire libraries could be crammed with treatises devoted to the topic.

Dissatisfied with the lack of systematics in the overall sustainability debate, I embarked, a couple of years ago, on the quest of developing a rigorous common formalism, extracting the essence of all possible concepts. On the basis of such a formalism, the elaboration of 'mathematical sustainable-development ethics' becomes feasible[4,12].

Some central results can be illustrated in a two-dimensional 'theatre world' where sustainable development is played out as a strategic planning exercise (Fig. 3). Two important aspects should be emphasized. First, the overall co-evolution space includes several unpleasant domains: apocalyptic zones as exemplified by the Martian regime (hypothetically attainable through a run-away cooling-chamber process), or the Venusian regime (hypothetically attainable through a runaway greenhouse process)[16], and catastrophe zones, where humanity might subsist, but in a miserable manner. Second, there exists a non-trivial subspace, the 'accessible universe', which consists of the ensemble of all realizable future co-evolution paths. These are generated by distinct management options contained in the strategic pool at the disposal of the global subject. Note that 'business as usual', that is, planless ecosphere transformation through individual opportunism, is definitely one of these options.

Five competing paradigms for sustainable development can be identified. (1) Standardization — prescribing an explicit long-term co-evolution corridor emanating from P_0 in Fig. 3. (2) Optimization — getting the best, that is, maximizing an aggregated anthroposphere–ecosphere welfare function by choosing the proper co-evolution segment over a fixed time period. (3) Pessimization — avoiding the worst, that is, steering well clear of catastrophe domains, allowing for the possibility of bad management in the future. (4) Equitization — preserving the options for future generations, not contracting the 'accessible universe' over time. (5) Stabilization — bringing the ***N–A*** complex into a desirable state in co-evolution space and maintaining it there by good management.

So, here is the menu from which humanity can select its master principle, or suitable combinations thereof, for Earth-system control. The formal elaboration of these paradigms and putting them into operation using, for example, EMICs, is a highly non-trivial exercise. And there still remains the question "What must we do?". It would be foolish to try to answer this comprehensively, but a few eclectic suggestions may give an idea of the scope of the challenge. I give these in descending order of speculativeness:

Optimization. The present geostrategic design of the ***N–A*** complex is not optimal. The industrialized countries dominate the fields of agricultural production, technological innovation, environmental protection, tourist services and many other areas. This implies not only considerable inequity across the Earth's population, but also unstable distortions of the natural web of energetic and material fluxes. A global redesign could aim at establishing a more 'organic' distribution of labour, where the temperate countries are the main producers of global food supplies, the sub-tropical zones produce renewable energies and high technology, and the tropical zones preserve biodiversity and offer recreation.

Stabilization. Why should Prometheus not hasten to Gaia's assistance? Geoengineering proposals have become popular as a way of mitigating the anthropogenic aberrations of the ecosphere. One interesting idea features iron fertilization of certain ocean regions to stimulate the marine biological pump which draws down CO_2 (ref. 24). And Russian scientists are currently elaborating a repair scheme for the ozone layer using orbital lasers. But we can also think of proactive control of natural planetary variability: insights acquired during the present climate crisis may enable humanity to suppress future glaciation events by judicious injection of 'designer greenhouse gases' into the atmosphere.

Pessimization. Least speculative and most essential is the creation of a manual of minimum safety standards for operating the Earth system. Human interference with the ecosphere may provoke the perhaps irreversible transgression of critical thresholds, bringing about qualitatively different environmental conditions on a large scale. The Intergovernmental Panel on Climate Change is now addressing risks like the shut-down of the ocean conveyor belt, the destabilization of the West Antarctic ice sheet, and the abrupt die-back of tropical forests due to super-critical global warming. The results of IGBP and related global research programmes will soon enable us to identify and respect 'guardrails'[25] for responsible planetary management.

In fact, the second Copernican revolution will be completed only if we take this responsibility — in spite of irreducible cognitive deficits as once lamented by Alonso X of Castile: "If the Lord Almighty had consulted me before embarking on the Creation, I would have recommended something simpler"[14].

H. J. Schellnhuber is at the Potsdam Institute for Climate Impact Research, Telegrafenberg C4, PO Box 60 12 03, D-14412 Potsdam, Germany.
e-mail: john@pik-potsdam.de

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Acknowledgements. I thank A. Block, M. Cassel, R. B. Cathcart, W. Cramer, H. Hoff, S. Lütkemeier, S. Rahmstorf, D. Smart, M. Stock, J. v. Braun, V. Wenzel and the entire IGBP community for intellectual and technical support.