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One Model to Fit All? The Pursuit of Integrated Earth System Models in GAIM and AIMES

Ola Uhrqvist*

Abstract: »Ein allumfassendes Modell? Die Suche nach integrierten Erdsystemmodellen in GAIM und AIMES«. Images of Earth from space popularized the view of our planet as a single, fragile entity against the vastness and darkness of space. In the 1980s, the International Geosphere-Biosphere Program (IGBP) was set up to produce a predictive understanding of this fragile entity as the 'Earth System.' In order to do so, the program sought to create a common research framework for the different disciplines involved. It suggested that integrated numerical models could provide such a framework. The paper historicizes the formation of the present ways of thinking about how the components are combined to produce policy-relevant knowledge about the 'Earth System.' The empirical basis consists of project documentation, publications and interviews from the Task Force on Global Analysis, Interpretation and Modelling (GAIM) and the project Analysis, Integration and Modelling of the Earth System (AIMES). Within the IGBP GAIM and AIMES fostered the advancement of 'Earth System' modeling. The paper divides the development of 'Earth System' modeling up into three phases. Research of the first phase mainly concerned the interpretation of model behavior (1984-1997), in the second phase integration and 'Earth System' analysis was placed at the center of research efforts (1998-2003). In the third phase AIMES scientists explored the consequences of incorporating humans as a dynamic component in the 'Earth System' (2004-). This transition shows that redefining the global environment in increasingly complex terms altered the role of modelers and predictability of the 'Earth System.'

Keywords: Earth governance, political history, computer modeling, International Geosphere-Biosphere Program, predictability, earth sciences and social sciences.

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1. Introduction¹

In contemporary environmental discourse, images of the ‘full Earth’ and ‘global change’ are invoked to remind us of the dangerous effects of excessive resource use and the need to devise governance systems able to navigate safely within the boundaries of the planetary life support system (Rockström et al. 2009; Reid et al. 2010). In the process of producing scientific knowledge able to advise decision-makers on how to simultaneously deal with issues concerning sustainability and development, the major funders of global environmental change research, such as the United States National Science Foundation, the United Kingdom’s Natural Environment Research Council and governmental research councils from the world’s major economies, which are organized in the Belmont Forum, recently found it reasonable to expect “an overarching framework, Earth System Analysis and Prediction System (ESAPS), to integrate and catalyse these priorities into a seamless, holistic environmental decision-support system” (Belmont Forum 2011, 2).

Future Earth, the new international research program on global change, endorses this ambition (Future Earth Transition Team 2012). This scientific initiative is a merging of the three programs International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on global environmental change (IHDP), and DIVERSITAS (an international programme of biodiversity science) into a single program. This program is designed to find ways to inform decision-makers and aid them in the management of global environmental and social change. At first glance, it may appear that a decision support system that embraces all relevant components required to address global sustainable development is exactly what is needed; however, historical and social studies of science remind us that concepts, such as the concept ‘global’ (Hulme 2010), the narratives arranging them in meaningful contexts (Höhler and Ziegler 2010) and even the problems that need governance (Rose and Miller 2008, Lövbrand; Stripple and Wiman 2009) are far from pre-given.

Departing from the vision expressed by the Belmont Forum in 2011, this article draws on the findings of the historical and social studies mentioned above and it aims to trace the history of the idea that a holistic and seamless decision support system is both feasible and desirable: “Efforts to produce an integrated model of the earth’s geosphere, hydrosphere, and biosphere should succeed” as one of the early IGBP papers argued; it is suggestively entitled: “One Model to

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Fit All” (Fisher 1988, 52). This article covers the years between 1982 and 2012 and unearths a history of shifts and ruptures in the discussions within the IGBP on ‘Earth System’ models and on the production of those models.

2. The Pre-History of IGBP

The scientific ambition to produce an integrated account of the ‘Earth System’ fits the growing attention paid to global problems and sustainable development. Examples of this global perspective may be found in the reports from the United Nations summits on human-environment relations, *Only one Earth* in 1972, *Our common future* in 1992 and *The future we want* in 2012 (Linnér and Selin 2013); a single, united population inhabiting a single planet needs to govern its own future. At the most recent of these conferences, the concept “planetary boundaries”, fostered in ‘Earth System’ science, was suggested to support a reorganization of global environmental governance (ICSU 2011). These scientific efforts never reached the final document, but conceptualizing the planet as one troubled interlinked system was strongly forwarded (United Nations 2012).

Since the late 1960s, the fear of global resource scarcity in light of a growing global population spurred popular as well as scientific discussions concerning the carrying capacity of the planet. Catalyzed by images of the Earth taken from space, the world, i.e. the ‘global,’ was increasingly seen as a single entity and the planet was discussed in terms of ‘Spaceship Earth’ i.e. a machine in need of management and repairs (Höhler 2008). In contrast, earlier research had predominantly aimed at social, political and economic changes on a global level (Price 1989). The notion ‘global’ thus had pointed to human wellbeing and geopolitics primarily.

Research related to the global environment has roots in the Cold War era and efforts at managing a global battlefield. One significant example is the International Geophysical Year (IGY) in 1957-58, a project which is often referred to as a success for scientific cooperation as it was carried out in the face of the struggle between the rivalling superpowers (Aronova et al. 2010). The exploration of the global atmosphere in view of launching intercontinental missiles also spurred a significant amount of interest from military forces around the globe, and the efforts at mapping potential battlefields during the Cold War also brought about mapping of most parts of the global environment from 1946 and onwards (Doel 2003).

Early scientific efforts aimed at assessing the Earth’s capacity to support human wellbeing were coordinated by the International Biological Programme (IBP) between 1964 and 1974. The IBP popularized a rendering of ecosystems as calculable energy systems moving towards optimal balance (Worster 1994). This holistic perspective was taken further by Lovelock (1979, 2000), who argued that life shaped optimal living conditions.

While the research carried out during the IGY and within the IBP sought to understand parts of a global environment as moving toward a state of balance, research took a turn toward complexity and chaos in the 1980s (Dahan 2010). With this backdrop, IGBP research on global change was supposed to bring together the parts earlier studied by IGY and IBP to a holistic perspective on the global environment. The term global change, previously developed by social and political sciences, was now adopted as an overarching concept by natural science. The natural-science framing was introduced at a NASA workshop in Woods Hole in 1982, and articulated global change as a threat to the habitability of the Earth: A threat that called for “an understanding of the overall system” (Goody 1982, iii). Rapid improvement of satellite and computer technology had just made integrated global models a desirable tool for decision support (Goody 1982; Malone 1985). The scientific rationale was accompanied by changes in the funding of global research. In 1984 and 1985, the United States and the United Kingdom withdrew from the main sponsor of international environmental research, the United Nations Educational and Scientific and Cultural Organization (UNESCO). Therefore, it has been argued that IGBP was an initiative to govern the research funds that became available (Dickson 1986). This proved to be true: Two years later in 1986, as the International Council of Scientific Unions (ICSU) convened in Bern, the IGBP was mandated to coordinate an international scientific community.

Tracing the history of system integration efforts through the eyes of the IGBP directs attention to the Task Force on Global Analysis, Interpretation (Integration since 1998) and Modelling (GAIM). In 1990, the IGBP was organized around a framework of six Core Projects, with each focusing on different components of the biogeochemistry, ecology and hydrology of the ‘Earth System’; the integration of these components was foregrounded as the major scientific contribution of the IGBP. In this heterogeneous but natural scientific landscape, GAIM was set up to integrate the work of all the projects into coupled ‘Earth System’ models and provide them with predictive capacity (IGBP 1990). About a decade later, the first acknowledged ‘Earth System’ models were introduced and GAIM was refocused under a new name, Analysis, Integration and Modelling of the Earth System (AIMES). Starting in 2004, AIMES provides the main venue for this study.

3. Empirical Base and Methodological Approach

The reports and newsletters of the IGBP (1986-2012), GAIM (1997-2003) and AIMES (2004-2012) constitute the empirical foundation of this analysis, which also includes empirical data on AIMES through the endorsed projects Quantifying and Understanding the Earth System (QUEST) and Integrated History and future Of People on Earth (IHOPE). Data was gathered during eight semi-

structured interviews with researchers at key positions in the projects, e.g. members of the Task Force or the scientific steering committee of the IGBP complement the documents.

The documents have been studied as remnants of local practices directed at knowing 'global change' rather than as the opinions held by individuals (Dreyfus and Rabinow 1983). The material is processed in three analytical steps, where the first aims to establish the major events and shifts in approaches as expressed in key documents, i.e. the self-evaluations of the participants. The second step engages the empirical material at a more detailed level and aims to establish how these shifts and events were connected to each other and to modeling practices. When tracing the scientific discussion, this "how" tends to alternate between problematizing past practices and suggesting solutions. This step of the analysis draws on internal discussions recorded in project newsletters and workshop reports. Equipped with these detailed results, the third step proceeds to interpret the discussions held on the topic of how to produce 'Earth System' models, and aims to identify shifts in the representation of the 'Earth System' and the kinds of expertise connected to the production of policy relevant knowledge. In this step of the analysis, phenomena such as the biosphere and practices such as modeling are continuously rendered problematic in relation to each other and in relation to the desired effects (Bacchi 2012).

Tracing the history of 'Earth System' modeling through the IGBP draws on an understanding of an inextricable unity of power and knowledge (Foucault 1998). The analysis utilizes Foucault's (1991) account of Governmentality and suggests that the produced rationalities makes the planet knowable as the 'Earth System' and, thus, manageable or governable in the sense that they allow for integrated or even seamless models in which it is possible to make strategic calculations of the effects of different policies. Knowledge produced using such models could potentially inform decision-making related to the global environment. A more subtle effect of modeling is that it may come to shape new ways of thinking. The author of this paper agrees with Edwards (2001), who argues that modeling is a process of world building. When seeking to produce representations of reality, modeling directs the manner in which data is gathered, organized and used, i.e. it constructs reality. As these constructions enable reflections on possible futures, they are inherently connected to power (Ashley 1983; Gramelsberger and Feichter 2011). Thus, the process of making the global environment visible in the form of the 'Earth System' affects expectations on what kinds of knowledge decision-makers need in order to be able to act responsibly and legitimately.

Earlier studies of how global models reproduce particular worldviews (e.g. Ashley 1983; Hughes 1985) may be taken as a motive to take a closer look at the underpinning culture of the present 'Earth System' models. The historical tracing of the discourses concerning 'Earth System' modeling conducted in this paper add to a growing, heterogeneous body of literature which has emerged

following the expansion of the Climate System to the 'Earth System' in the atmospheric sciences (i.e. Paillard 2008; Edwards 2010; Dahan 2010). The climate-centered narrative is elegantly summarized by Gramelsberger and Feichter (2011, 8): "climate change and policy have turned the physics of the atmosphere and the ocean into a multifaceted picture of the Earth system." The paper complements the climate-centered narrative by analyzing the efforts to know and predict Biosphere-Geosphere interactions. This is all the more important because, at the time the concept was coined within the IGBP, 'Earth System' modeling did not primarily focus on the climate (Kwa 2005; Bolin 2007).

The following sections divide the development of 'Earth System' modeling into three phases. In the first phase, scientists mainly dealt with the interpretation of model behavior (1984-1997). Here, experts on Earth's subsystems dominated the agenda and the 'Earth System' was studied as a weakly coupled compilation. The second phase placed the ideas of system integration and Earth System Analysis at the center of attention (1998-2003). Here, experts on complex systems modeling played a key role, and the governable 'Earth System' was argued to rely on knowledge about the system as a whole. The third phase explored the consequences of inviting humans as a dynamic component in the 'Earth System' (2004-). This shifted the required expertise again, because detailed process understanding is argued to rest on a broad range of social and natural sciences. The three different approaches to modeling methods and the relevant expertise also show changes in the ontology of the 'Earth System.' The final section of the paper reflects on how integrated global models produced new understandings of the notion of global, from thin to thick, and the expertise able to give scientific advice to decision-makers in times of global change.

4. Interpretation to Set a Stage for Synthesis (1984-1998)

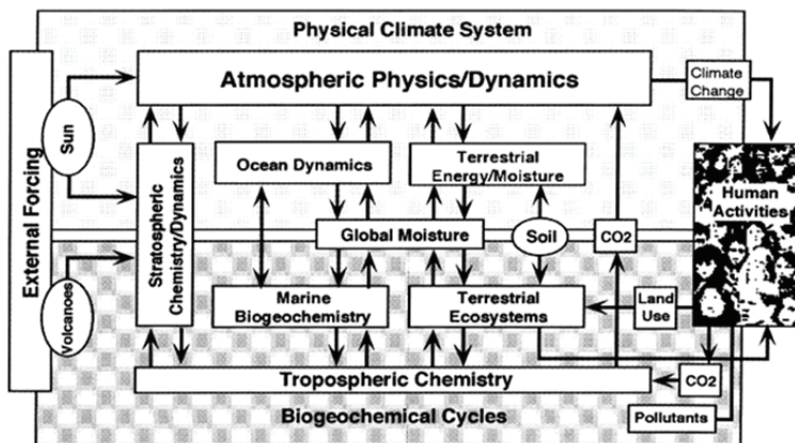
The goal of the IGBP to turn existing conceptual 'Earth System' models into predictive models motivated the development of a new and more holistic approach to the study of global natural dynamics (IGBP 1986). However, which components to include and how they were supposed to interact had still not been settled. The first of the three phases started in 1984 with the aim to create integrated models on a global scale. A key problem of this phase concerned fitting an 'Earth System' framework with the required expertise, which was organized in different research communities. The phase ended in 1998 when the IGBP started the process of synthesizing the results.

Up until this point, GAIM functioned primarily as a bridge between projects in the wider IGBP structure. This meant that it supported interaction over project boundaries and between research groups.

IGBP representatives argued that an eventual success for the IGBP relied on finding convincing ways to integrate sub-components into ‘Earth System’ models. GAIM was the part of the IGBP assigned with the task of carrying out the effort “required to ensure that the knowledge gained about the components of the Earth system fits into a globally consistent and internally compatible description” (IGBP 1990, 8.1-3). From the outset of the planning process, computer models were expected to foster “a common lexicon, if not a single language” for the program participants (IGBP 1986, 9).

The components to be made compatible with one another were based on what had become known as the Bretherton diagram, which had been developed by NASA (see Fig. 1). This wiring diagram outlines an ‘Earth System’ built on physical and biogeochemical sub-systems and establishes relationships between these sub-systems. The ‘Earth System’ was a novel concept which had just been coined by a working group led by Francis Bretherton (NASA 1986). Here, the analogy ‘Earth System’ was translated into the “Earth system”, which denoted an existing object. As a concept intended for use in discourses concerning interacting components, the ‘Earth System’ organized the global environment as coupled boxes.

Figure 1: The Bretherton Diagram of the Fluid and Biological Earth Processes



Source: NASA (1986, 19).

This view of the global environment as a machine of coupled sub-systems was closely connected with the experts involved in trying to predict its behavior. Introducing the ‘Earth System’ as a new object of knowledge spurred competition over epistemic authority. At this time, the IGBP working group “Global Geosphere-Biosphere Modelling”, from which GAIM would evolve, engaged famous meteorologist Bert Bolin, atmospheric scientist Francis Bretherton from NASA and other experts closely connected with the Intergovernmental

Panel on Climate Change (IPCC) Working Group 1. The IPCC Working Group 1 had been established in 1988 to assess the physical scientific basis of climate change (Bolin 2007, 53). All working group members except two were either lead authors or co-authors in the first assessment report of the IPCC. This working group exemplifies the close personal connections and institutional overlaps between research programs, national institutions and assessment organizations but also the high status of the group.

The group of distinguished experts on matters concerning global modeling presented their reflections at the first meeting of the IGBP Scientific Advisory Council in Stockholm in October 1988. At this point, two competing approaches were considered for use in the modeling of the 'Earth System.' The first was to act in parallel with physical climate research and reserve modeling for those sub-systems which had not yet been studied by the World Climate Research Program (WCRP). The second approach was to model the full 'Earth System,' including the climate. The working group chaired by Bretherton "believed strongly" in the full modeling approach as the only "productive option," at least in the long run (IGBP 1989, 117), which also fits well with a shift in how the working group articulated its task and an emerging tension toward IGBP projects focused on specific components.

Emphasizing "the overarching role of modeling in the IGBP" (1989, 41), the meeting signaled a shift in the approach to the object of study. The proposition to include the climate in the work of GAIM testified to the epistemic ambition to include climate science into the 'Earth System' framework of co-evolution. Still it was deemed essential to maintain a close cooperation with the modeling activities of the WCRP (IGBP 1989). Here, the epistemological tensions between different perspectives on how to study the 'Earth System' became obvious. When the group met at Harvard in February 1988, focus had been placed on the development of global biogeochemical cycles, i.e. on improving the understanding of the components (IGBP 1988). Half a year later, the focus was shifted toward improving the understanding of the 'Earth System,' i.e. the understanding of the whole (IGBP 1989). The first approach gave priority to the components whereas the second favored a holistic perspective of the system.

The question of which methods to use in the production of integrated global climate models produced tensions between WCRP and IGBP. During the first decade of the existence of the organization, the IGBP executive officers experienced that a full integration of climate and biogeochemical models was resisted by the WCRP on the grounds of methodological and theoretical incompatibility (Interviews with Steffen 2009; Rosswall 2012). It clearly was not self-evident how the boxes in the Bretherton diagram were to be combined. Also, the predictability of the 'Earth System' was in itself a "major issue for research" (IGBP 1989, 117).

The central role of GAIM as a supplier of expertise on the 'Earth System' was contested within the IGBP as well. When GAIM was formally launched in

1992, the approach suggested in November 1988, i.e. modeling the 'Earth System' as a whole, had to give way to a more decentralized strategy. As was later described by the first chair of GAIM, mathematician Berrien Moore, the planned modeling of the 'Earth System' was "a new kid on the block" that challenged the scientific communities already engaged in modeling global water and carbon cycles (Interview with Moore 2012). Thus, GAIM was not seen as an unproblematic continuation of the practices of integrating the biogeochemical cycles.

Contesting views on where to find the required expertise on global modeling changed the role of GAIM. The working group was relegated from its strong central position in the planning phase to a supportive role, mostly consisting of facilitating the integration of Core Projects. According to the scientific rationale of the early 1990s, to which the program politics of the IGBP adhered, it was most promising to work towards fully integrated 'Earth System' models based on the biogeochemical cycles addressed by the Core Projects. This shift was also reflected in the fact that GAIM went from being a proposed IGBP Core Project in 1990 to a Task Force of the IGBP Steering Committee in 1992 (Moore 1992). The expertise on 'global change' remained within the already existing research communities as represented in the Bretherton diagram. As one of its early members, Martin Heimann (Interview in 2012), later described, the newly established GAIM understood its role to be that of a forum, i.e. facilitating discussions and coordination between the research environments driving the development of the modeling in the different IGBP Core Projects.

When the "truly global models" of the IGBP were first launched in the 1990s, they were "available only in the form of crude box-models" (IGBP 1990, 8.1-10). On the boundaries of these boxes, GAIM found itself a role as a developer of methods for evaluating models by comparison. GAIM translated a method used by climate physicists for systematically testing the performance of atmospheric models to the context of bio-geochemistry and ecology. For years to come, model intercomparison projects turned into one of the most frequently discussed activities in GAIM. Early examples of this are the workshops held in Potsdam in 1994 and 1995 where global models for simulating net primary productivity of ecosystems were evaluated (IGBP-GAIM 1999).

The problem of evaluating the quality and realism of models brought about a strong emphasis on making the results visible. As to validation methods, a major step was taken with the ability to represent model runs as global maps and compare these with observations from space. Moore (Interview in 2012) remembers this new visibility as a great breakthrough enabling modelers to assess the results of global model runs (i.e. distributions of ecosystems) as spaces rather than as budgets. Earlier, the results of model runs yielded a global or, at best, regional account of biomass, carbon stocks and flows presented numerically. Resembling economic accounts they underpinned discourses on carbon budgets and, as shown by Lövbrand and Stripple (2011), the administra-

tion of climate change. With the new, spatial representations the impact of local/regional diversity could be assessed. The maps also offered a more realistic representation, which opened for intuitive interaction and, thus, enabled the results of global simulations to travel beyond the modeling community and into public deliberations.

In the first phase, interpretation of model runs was a key activity. Models were used to test the understanding of global biogeochemical processes by comparing the simulations to empirical observations. The work GAIM performed at the boundaries of the boxes enabled the scientists to trace biogeochemical flows between components of the 'Earth System.' In dealing with these flows, GAIM sought to minimize the risk of blind spots by viewing the system as a whole; whereby they found explanations for the divergence between simulations and observations by identifying the missing pieces (Woodward 1992). In this work, the holistic approach and the need for modeling made the Bretherton diagram a problematic framework for 'Earth System' models. The assumed co-evolution of the components of the 'Earth System' (IGBP 1994, 12) made any consideration of an isolated cycle seem fruitless as it could not be properly understood without simultaneously considering other interacting cycles. In the presentation of GAIM, the assumed "co-evolution of different components of the Earth System" was presented as a key scientific question (IGBP 1994, 12). Integrated modeling at the global scale here embraced a whole system approach. Approaching the system as a whole was rendered necessary to trace and explain the unexpected amounts of substances in certain locations. Interpretations of the model runs increased the amount of relevant feedback and thus produced a rationale for the closer coupling of the boxes in the Bretherton diagram.

5. Integration and Earth System Analysis (1998-2003)

The start of the IGBP program synthesis in 1998 marks the beginning of the second phase in this historical account, which traces the idea of the feasibility of a seamless, holistic environmental decision support system. The second phase is characterized by a strengthened system perspective in which it is argued that "more focused supporting questions" could be asked in a top-down manner (Moore and Sahagian 1997, 2). These new questions were constructed with the 'Earth System' as the object of analysis; a shift that was expected to influence the research agendas of the Core Projects. The Scientific Committee of the IGBP began to place focus on research questions around the 'Earth System,' thus producing a discourse that would inform a radical reconstruction of the IGBP.

The on-going synthesis of the results of IGBP had led to program-wide discussions of possible ways to connect heterogeneous components of the Brether-

ton diagram (see Fig. 1) and soon GAIM was “redirected to address the system as a whole” (Moore 2000, 2). One part of GAIM’s new goal was to produce concepts usable in global environmental management. Writing as the new chair of GAIM, systems analyst Hans Joachim Schellnhuber proposed *Earth Systems Analysis* as a way “to yield a unified formalism for describing the make-up and functioning of the ecosphere machinery” (Schellnhuber 2000, 3).

Figure 2: Earth System Analysis and the Copernican Revolution



Source: Schellnhuber (1999).

Schellnhuber (2000, 4) drew on the support of “top representatives and executives of the IGBP” who had gathered at a GAIM meeting “concluding unanimously that GAIM shall become the central driving force for Earth System Analysis.” This approach had been developed at the Potsdam Institute for Climate Impact Research and boldly described as “a second Copernican revolution” where the view from space would provide the backdrop for a new understanding of both humans and the planet Earth (Schellnhuber 1999). As the Earth System Analysis was introduced in *Nature*, the perspective was illustrated by depicting a surgeon, located in space, looking into the dynamics under the opened atmospheric skin of the Earth (see Fig. 2). The picture suggested that the ‘Earth System’ analyst was a planetary surgeon embodying the expertise required to keep the living planet healthy. It also emphasized that increasing focus was placed on the application of knowledge of the ‘Earth System.’

Uhrqvist and Lövbrand (2014) discuss the picture as an extension of the Foucauldian concept of 'Biopolitics.' While the governing rationale of the modernizing states of the nineteenth and twentieth centuries was directed towards knowing and optimizing the 'population,' it appears that the governing rationale of the twenty-first century has expanded to include the management of the living planet. The image below is a powerful visualization of the conditions for responsible management of global change beyond the boxes of the Bretherton diagram. It points to the need of the 'Earth System' analyst to know integrated global dynamics as seen through macroscopes located in space, in order to maintain a steady hand.

"Unified formalism" sought and found a methodology for integration in the theory of complex systems (Schellnhuber 2000, 2). Against the backdrop of accelerating global change, GAIM merged the demand for science-based policymaking with integrated global models as an indispensable tool for producing the needed knowledge. Reaching the next step in the understanding of the global integrated environment was considered to depend on the creation of new research questions; questions which would center on the 'Earth system' as a whole. Inspired by the authoritative and visionary set of questions famously outlined for the field of mathematics in the twentieth century by David Hilbert, GAIM proposed their own 'Hilbertian questions.' The background of these questions resonates well with the task undertaken by GAIM and exemplifies the central position of mathematics in the Earth System Analysis. At a conference held in Paris 1900, German mathematician Hilbert argued that all scientific disciplines require inspiring questions in order to hold together or, else, they risk the "fate of those other sciences that have split up into separate branches" (Hilbert 1902, 478). Whereas Hilbert sought to stop an on-going fragmentation of mathematics, GAIM proposed the twenty-three questions to envision "the advent of a unified Earth system science" (GAIM 2002, 1). The questions were organized in four categories, analytical, operational, normative and strategic (GAIM 2002). Questions pertaining to policy research are, as a rule, found in the strategic category. Openings for other social sciences were, on the other hand, included as the 'Earth system' was broadened to relocate the human dimension from the boundaries of the Bretherton diagram to become a co-driver in the 'Earth system.'

GAIM's discussions about how to model and who to do so are very abstract. On a conceptual level, they inquire into what the 'Earth system' is and ask questions about the expertise needed to produce science based decision support. The call for a unified formalism and inclusion of human dimensions implies that humans or at least societies have to be fitted into this universal mathematical frame. The 23 GAIM questions emerged at the intersection of three issues: modeling the planet as a single system, the possibilities and limitations of numerical models, and the urgency of addressing questions on global sustainability. In the rationale of GAIM, successful modeling activities were the

results of more streamlined research projects which started in the desired goal and progressed towards an understanding of the full system rather than starting in a set of integrated questions and working toward synthesis of these questions. The metaphors connected to the Bretherton diagram, which had been central to the organization of knowledge in the early days of the IGBP and which described the planet as an assembled piece of machinery, now changed. Dressed in a more organic suit, this machine had been reconceptualized into a body with “weakly coupled organs” (GAIM 2002, 10).

In the subsequent problematization of the components required to model the ‘Earth system,’ GAIM argued that the primary methods used to identify the ‘organs’ and their boundaries had earlier been common sense observations and institutional convenience. In Foucault’s (1991) terms, this is to say that heterogeneous relations had been made knowable as objects (organs) within earlier regimes of government and hence had attained their characteristics in relation to problems other than the understanding of the ‘Earth system.’ According to GAIM, it no longer made sense to build on these components in the production of global integrated models. Instead, GAIM proposed the development of “Earth system models based on a “few dozen key processes,” arguing that “a bottom-up procedure of multi-scale analysis of the fundamental equations of motion” (GAIM 2002, 10) better mimicked system behavior. In line with Edwards’s (2001) understanding of modeling as world-building, GAIM suggested that what made sense in modeling practices should inform the way the planet was observed: Good models had the power to destabilize long-standing components.

GAIM also proposed a new mode for properly facilitating model interaction between components in the ‘Earth system,’ in which coupling of weakly connected organs were no longer considered relevant to the further development of integrated ‘Earth system’ science. These rationalities resonated well with how the IGBP visualized its new focus in the second phase of the program, “highlighting the complexities of and cross-scale interactions between the different elements of the system [...] with a superimposed grid indicating the importance of Earth System modelling” (IGBP 2006, i).

Discussions about which components and processes were deemed relevant and the choice of modeling methods also demonstrated changes in the way GAIM envisioned its role both within and outside of the IGBP. GAIM endorsed a bolder position propagating the importance of models not only in relation to the other projects, but in relation to policy making in general. When introducing Earth System Analysis, Schellnhuber (2000, 3) motivated the need to address the planet as a whole through integrated models by arguing that integrated models “address the challenge of sustainable development in a non-sense way.” This rationale for global knowledge production elevated dynamic, integrated, and global computer models – and modeling expertise – to a place at the center of the management of global change and sustainable development. Social and environmental needs for sustainability were to be translated

into 'Earth system' models providing the basis for no-nonsense decision-making.

The elevated position of expertise in modeling and model interpretation is further visible in the suggestions for first cognitive principles. Schellnhuber (2000, 3) proposed "deducing the macro-options for future ecosphere-anthroposphere co-evolution from first cognitive and ethical principles." This refers to interpretations of the model runs visualized as "a phase space structure of switches & thresholds" (GAIM 2002, 10). A 'phase space' displays all possible positions of a system, including the tipping points where the system may begin to behave differently. Connected to sustainable development policies, this first ethical principle, the macro-perspective and the built-in assumptions about the dynamics of the 'Earth system' place a large amount of power in the hands of computer models which are beyond the reach of interpretation by people outside the expertise on 'Earth system' modeling. Schellnhuber (2007, xx) later used a metaphor to describe the challenge of interpreting the results produced by the models by comparing it to the mirror of the Elf queen Galadriel, which showed the past, the present or even any of several possible futures; she reminded those who chose to peer into its depths that whatever they thought they saw, not even the wisest among them could know for sure what it was.

As these kinds of models aspire to be the only proper avenues to reach an understanding of global change and to address policy options in a no-nonsense way, they place a lot of confidence in formal mathematical analysis. When it was claimed that model results regarding present and future global change were relevant for policy-making, the problem of climate change broadened to create a political space where "what could be known" produced a "should be recognized". Hence, assembled 'Earth system' models are windows into the future which were able to assess the effects caused by changes and to do so across various sectors of global knowledge – if looked at in the proper way. Global knowledge had to be more than knowledge encompassing the whole face of the planet. Here, in contrast to the global biogeochemical cycles, 'global' had to consider all relevant processes governing environmental change: In this view, policy makers heavily relied on global integrated models for the pursuit of the common good.

The self-positioning of the GAIM modelers as crucial actors pointed to a recurring theme: the problem of the old disciplinary sedimentation, which had to be overcome by an extraordinary ability to think outside the box. As the modelers of GAIM continuously worked on ways to integrate and validate new components in the modeling of the 'Earth system,' they often returned to the explorative approach characterizing their work (Prentice 2003; Interview with Heimann 2012). This explorative approach was supported by their position within the structure of the IGBP. The "think-tank character" of GAIM gave its relatively few members the opportunity to be flexible (Schellnhuber 2000, 2). The role as scientific spearhead thus positioned the group in relation to other

IGBP projects and its own history; one characteristic of a good GAIM 'Earth system' modeler was that he/she was able to open new avenues which no one else could reach (i.e. Prentice 2003). In contrast, discussions rarely mentioned perfecting or fine-tuning established practices. Compared to its first five years, the second period of GAIM was characterized by a bolder approach to both integrated models and the other projects within the IGBP.

6. Incorporating the Human Dimension (2004-)

The first phase developed around the argument that better knowledge of the global life-support system required knowledge of the how the systems are integrated. In the subsequent development of expert knowledge on how to couple models, the distinct boxes of the Bretherton diagram received an increasing amount of criticism. During the second phase, Earth System Analysis translated this problematization into the position that the 'Earth system' had to be understood as one self-regulating system, which included human activities. The third phase continued to promote the holistic perspective found in Earth System Analysis. However, exploring ways to operationalize the incorporation of humans into the analysis came to decentralize, or at least broaden, the expertise and the scope of the analytical approaches used in 'Earth system' science.

The synthesis of the IGBP followed the rationale of the Earth System Analysis when it argued that including humans as system drivers required "the construction of a single, coherent framework built jointly by social and natural scientists" (Steffen et al. 2004, 284). The IGBP reorganized the program structure between 2002 and 2004 to place the 'Earth system' as one entity at the center of the research design and, subsequently, refocused the projects to provide answers to the challenges outlined in the 23 strategic questions of GAIM. The new research design resonated among decision-makers and was hence welcome. Evaluating risks and comparing policy options to manage and/or mitigate those risks required the inclusion of human activity (AIMES 2010, 7). Compared to the first phase of 'Earth system' modeling, this represented a change in the entity to be understood and predicted.

The new direction in 'Earth system' modeling also rearranged the arena for knowledge production. GAIM was replaced as the integrative modeling unit of IGBP by Analysis, Integration and Modelling of the Earth System (AIMES). The name shift was intended to highlight the ambition "to integrate human interactions" (AIMES 2010, 5). IGBP expected AIMES to provide a formal bridge across the global environmental change programs. This never took off since the World Climate Research Program prioritized to continue focusing on physical global climate modeling, and cooperate with IGBP where needed (Interview with Steffen 2009). Skepticism regarding the value of such grand modeling approaches restricted resonance in the wider International Human

Dimensions Programme (IHDP) (Interview with Jäger 2012). Modeling is barely mentioned in the last strategic plan of the IHDP (2007). Despite cross-program integration not taking off, cooperation continued with coupling carbon-climate models and model intercomparison. Hence, holistic ‘Earth system’ modeling remained an IGBP concern.

The new major challenge for AIMES was to find ways to understand and quantify human activities and ecosystems as driving components in ‘Earth system’ models. This task required the integration of new fields of expertise in the modeling projects (AIMES 2010, 1). AIMES engaged in a range of social and natural science projects. Arguably, the Integrated History and Future of the People on Earth (IHOPE) project, co-sponsored by the IGBP project Past Global Changes (PAGES) and the IHDP, was the most innovative. The IHOPE project was designed to develop global datasets and a process understanding of socio-ecological systems based on long-term interactions between humans and their environments (AIMES 2010, 17). As argued by AIMES, the perception of humans as “fully embedded players in a coupled, dynamical system [...] is challenging the way in which research on the analysis and modelling of the Earth system is organized” (AIMES 2010, 2).

Understanding of humans and their modified ecosystems as driving components of ‘Earth system’ dynamics problematized the historical datasets which had previously been used to calibrate ‘natural’ ecosystem dynamics. Instead, detailed data about historical co-evolution between societies and their environments became important (AIMES 2010, 9). The ambition to understand and predict coupled human-environment systems led to collaborations between experts from a broad range of fields such as paleontology, archaeology, history, ecology and land use science, and the IHOPE project set out to achieve the ambitious goal of integrating past, present and future of human-environment interactions. It was argued in the IHOPE research plan that the creation of an analytical framework able to “integrate perspectives, theories, tools and knowledge from a variety of disciplines spanning the full spectrum of social and natural sciences and the humanities” (IGBP 2010, 1) was required – hence assuming that the mentioned fields of expertise can be fitted into a modeling framework.

IHOPE suggested a study of the rise and fall of civilizations in order to integrate dynamics at different scales and to relate them to present challenges of global environmental change. In practice, this came to motivate research designed to start in local and regional processes intended for later aggregation to the global scale (IGBP 2010, 15). In an Anthropocene ‘Earth system,’ the IHOPE project had to calibrate and test “integrated global ‘Earth system’ models that contain a range of embedded hypotheses about human-environment interactions” (IGBP 2010, 7). The integrated models of IHOPE were supposed to test hypotheses derived from different approaches to past agricultural activities and their relation to the climate. Just like other models in the history of the

IGBP, they were thought to bridge disciplines based on their apparent lack of bias. In this paper, trust as an outcome of modeling is interpreted as a co-production of relevant data and rationales which support certain methods of modeling. The attributed neutrality favors quantitative approaches due to the fact that it requires access to huge amounts of data (e.g. Kwa and Rector 2010).

The IHOPE project used a terminology developed within ecosystem modeling and heavily drew on ecological concepts. Thus, the integration of social dynamics required some adjustments of terminology. First of all, the models needed to include a “social memory” as this was found to be an important part of the resilience and adaptive capacity of social systems (IGBP 2010, 9). Hence, in resonance with AIMES and IHOPE recommendations, models came to require data to span much longer periods of time and also to involve evolution of social systems. The memories of the populations were stressed as an important as well as challenging component in these systems. Experiences from modeling had shown that responses to external changes could not be predicted based only on present material conditions. These memories also provided a connection to governance and ecosystem management due to the fact that it brought in dynamic social networks with their “interplay between the individual (e.g., leadership), the emergence of organizational structure, institutional dynamics, and the power relations” (IGBP 2010, 10).

Secondly, understanding human-environment systems also questioned the timescales previously used; the 10-50 year time horizon of earlier observations and models on ecological resilience became problematic as it would not catch the “so-called creeping changes, and the acceleration of system dynamics” (IGBP 2010, 10). At the same time, simulations of technological dynamics had to enable long-term modeling of the human-environment system. As for the sudden shifts observed in these technological systems, it was argued that the only reasonable way forward was to rely on very complex relationships simulating path dependency and “systemic ‘choices’” (IGBP 2010, 11).

This paper examines the trajectory the idea of a seamless model took; it explores the different solutions people found to integrate all ‘relevant’ dynamics into a single model. Identifying the sequences of causation in the studied systems proved to be highly problematic. Scientists thus acknowledged that socio-ecological systems were complex. In addition to encouraging a turn toward complexity science, the IHOPE project envisioned a strong emphasis on finding ways to validate and interpret the results (IGBP 2010, 15). This was problematic due to differing views even over basic ontological assumptions. For instance, it remained unclear which historical information and processes would be relevant to observe (IGBP 2010, 19).

Despite the challenges facing the modeling activities, the IHOPE project members expressed high hopes regarding the possibility of using models as tools to facilitate constructive dialogues across the different disciplines and perspectives; tools which would eventually lead experts to converge on inter-

pretations of model runs due to an evolving common understanding of the connections within the human-environment systems. A radical approach suggested a “physics of society”, and the effort of finding ways to combine the laws of nature with the dynamics of society called for a start in individual relationships and self-organizing social relationships, groups and institutions (Dearing 2007, 28). This vision resonating non-linear Dynamic Systems Theory, General Systems Theory and cybernetics was popular in the early days of computer modeling (Bechtel and Hamilton 2007). It appears that the dream of a ‘unified formalism’ in Earth System Analysis still had resonance in the, broadly defined, development of ‘Earth system’ models.

In the realm of environmental governance, the shift towards slowly evolving human-environmental systems problematized the institutional design of societies. The research design of IHOPE was founded on the assumption that few, if any, linear relationships exist between environmental change and the effects on earlier civilizations. A closer analysis of why some civilizations collapsed in the face of certain environmental changes while others prospered was assumed to provide insights into the social dynamics affecting the resilience of societies (Redman et al. 2007). It would raise questions on “how modern societies may (or may not) be able to deal effectively with climate change” (IGBP 2010, 11). A key question asked by the IHOPE project was “whether or not multi-level governance becomes too slow to respond to the speed, frequency and unpredictability of environmental signals” (IGBP 2010, 10). According to the IHOPE rationale systems, analysis could adequately simulate the rise and fall of civilizations – in contrast to more traditional social science approaches based on studying single components of these systems. The modeling community claimed to have acquired a unique tool which was able to provide advice on policy-making; reasonably, responsible governors would have to consider this black box before engaging in policy design.

From the outset, it has been the explicit goal of the IGBP to close the gap between science and policy by making its research results useful for decision-makers. Applied ‘Earth system’ science as envisioned by AIMES seeks to link ‘Earth system’ models to different assessment activities and translate “results into useable science for resource managers and decision makers” (AIMES 2010, 13). However, this has been acknowledged to be a difficult task. In knowing the ‘Earth system,’ especially with humans as drivers, “quantitative predictions tend to be both inherently uncertain and potentially misleading” (AIMES 2010, 15). As long as the audience is not familiar with how to use the results, the models will continue to give rise to a need for experts able to interpret these results and guide discussions.

The largest program related to AIMES which has synthesized its results is the UK based program Quantifying and Understanding the Earth System (QUEST). In 2010, AIMES and QUEST organized a joint open science conference at which the personal overlap was significant. The synthesis of QUEST

from 2012 offers an example of the close connection between 'Earth system' modeling and political rationalities. The authors object to statements that predictions made by 'Earth system' scientists represent a "misplaced technocratic worldview" (Cornell and Prentice 2012, 248) and state that such a control would require an "extraordinary level of social control." The conclusion drawn from the decade of work on integrated 'Earth system' models by QUEST was that the complexity and variability in the behavior of the system (both social and ecological) recommend us to keep a good margin to the tipping point that could shift the behavior of the planet into another mode of operation (Cornell and Prentice 2012).

This does not mean that 'Earth system' scientists have rescinded from their claim to being able to provide the necessary knowledge based on predictions. However, in relation to the problem of global change and an 'Earth system' dominated by humans, it appears that a new rationale is forming regarding how to interact with the global environment. This new rationale is well captured in a quote by Schellnhuber:

In fact, the best way of anticipating the future is by construction. Nobody is able to predict the precise position of a given dozen of individuals a week in advance under normal circumstances; however, the same task becomes fairly simple if one organizes a get-together with them at a certain location at the time in question (Schellnhuber 2007, xxi).

7. The 'Earth System,' its Experts and their Responsibility

The IGBP has justified holistic 'Earth system' science with the urgency to gain knowledge about and manage global change. Since 1985, urgency and relevance to policy-making have been invoked as important reasons for heading into uncharted scientific territory. Throughout this history, integrated global models formed one of the cornerstones in how the 'Earth system' has been constructed as a way to know and manage global change. After nearly three decades of 'Earth system' science, the major funders of research on global environmental change find it reasonable to expect the advance of "a seamless holistic environmental decision-support system" (Belmont Forum 2011, 2). In this paper, the mutual formation of a problem, an object and the expertise suitable to provide scientific advice have been analyzed through Foucault's (1998) lens of power/knowledge. On this basis, three phases could be distinguished.

Throughout the period, predictive models have been viewed as neutral testing grounds facilitating tests of process understanding against observations, and both the documents and the interviews refer to model intercomparisons as being very straightforward. The activity of modeling was framed as neutral, despite the fact that the rationale of AIMES acknowledges the need for different perspectives and methods for interpreting model output.

With regard to what was modeled, it may be noted that a shift in use of the word ‘global’ is found to be at the center of the discourse in this global knowledge production. During the first phase of GAIM, knowing global biogeochemical cycles meant knowing world-spanning cycles best observed from space; this is referred to as a ‘thin global.’ With the Earth System Analysis of the second phase, the meaning of the notion of ‘global’ shifted and came to represent the full planet, the life-support system or the planetary machinery. The “no-nonsens way” to know and govern global sustainable development that rested on Earth System Analysis reflects a ‘thick global’ due to its inclusion of a broader range of interacting processes and temporal scales.

Furthermore, the more complex and potentially unstable the ‘Earth system’ was rendered, the more important the continuous development of predictive models and observations of trends in the planetary dynamics became. Gradually, integrated computer models came to assume the position of indispensable technology for responsibly knowing and governing the ‘thick global’; with ‘thick global’ understood to be composed of human and natural processes operating at different time scales and spatial scales. Based on a ‘thick global’ and backed by the ontology of an integrated, calculable, global environment, ‘Earth System’ scientists proposed planetary boundaries as the organizing principle for global environmental governance (ICSU 2011), thus challenging existing governance systems.

Figure 3: Three Phases of ‘Earth System’ Modeling and Expertise

	1984- (GAIM)	1998- (GAIM)	2004- (AIMES)
What to know?	A ‘thin global’ notion – mostly visible from space	Earth from machine to organism, criticizing weakly coupled organs	A ‘thick global’ notion – including historical and social processes
How to know?	<i>Decentralized</i> – coupling of boxes in the Bretherton diagram	<i>Centralized</i> – universal formalism as in Earth System Analysis, seamless integration	<i>Decentralized</i> – A fully integrated Hu-man-environment system
Responsibilities of experts	Scientific; integrate understandings of biogeochemical cycles	Evaluating policy options from model ‘phase spaces’ using first order principles	Applied science; co-producing research questions

Who are the experts are is a central issue in scientific knowledge production. Drawing on a highly connected global system, the expertise emerging in global change research challenged established resource managers by problematizing the stability of components in society and nature. In this rationale, expertise on more local and sectorial scale management is still needed although global change discourse restricted the development of strategies to the spaces or corridors derived from global scale dynamics. Discourse on ‘Earth system’ models did not rely solely on confidence in scientific arguments; importance was also given to statements claiming that distinguished representatives from the fields

which were to be integrated participated in GAIM and AIMES. This suggests a concern for retaining scientific credibility needed to mobilize a broad support within the larger IGBP community. The mobilization capacities proved to be productive: the strong position of global integrated models twice reshaped the structure of the IGBP in line with current views of the modeling community. First, modelers reshaped the community around the Bretherton diagram; later they managed to reconfigure the IGBP according to the idea of complex human-environment system.

Although global change research has always related its goals to policy-making, most of the discussions found in the empirical material concerned the scientific sphere only. The prominent role of models appears to have been a catalyst for reflections regarding the true nature of the 'Earth system.' The tension between the results of model runs and the expected outcome triggered new questions. As humans were included in the analysis, the object of AIMES/IHOPE research changed to socio-ecological systems, which were analyzed with the aim to make them governable. Responsibly knowing these systems to facilitate governance included awareness of the slow as well as rapid processes able to cause sudden shifts. Compared to the understanding of natural processes, natural variations and non-linear behaviors called for studies over substantially longer periods of time in order to understand the direction and pace of natural and socially induced changes. Thus, the 'thickness' of the notion of 'global' increased in the sense that a longer time frame was required to explain observations of changes in land-use or institutions.

This raises the question of how well 'Earth System' modeling fits in interpretative frameworks centered on technology and the pursuit of control, which have been important components in modern societies in which numerical models have been tools often accompanied by metaphors of the machine (i.e. Kwa 1994). This is a fair representation of the early approach to modeling in GAIM, which was based on the Bretherton diagram and described planetary dynamics as the likeness of a machine with clear-cut components. As recognized by Dahan (2010), later forms of 'Earth System' modeling have been accompanied with the return of metaphors honoring Earth as a living being by replacing the machine with an organism. This corresponds well to the discussions within GAIM in which the approach of "weakly coupled organs" was questioned (GAIM 2002, 10) and the original goal of the IGBP, which included an 'Earth System' with a predictable future that gradually changed as more components were added (Uhrqvist and Lövbrand 2014).

The discussions on 'Earth System' modeling suggest that the initial goal of predicting the future of the system came to be transformed into an ambition to predict the behavior of the system. As a consequence, the idea of control has been transformed, which is mostly visible in the invitation of humans into the 'Earth system' via socio-ecological systems. As was stated in the planning phase of IHOPE, models can well assist in constructing desired futures, but

they cannot predict them. This does not mean that ‘Earth System’ science has given up on its ambitions to understand the dynamics of the planet. Although recent publications (e.g. Cornell and Prentice 2012) claim to have improved their understanding of what happens under certain conditions, knowing these conditions still appears to be highly problematic, particularly due to the effects of human activities. Instead, the ‘Earth System’ ontology popularized as the Anthropocene provides different sustainable paths surrounded by modeled tipping points; due to the degree of uncertainty, however, it is recommended to stay clear of these cliffs. ‘Earth system’ science also aspires to provide knowledge of mechanisms able to steer the system in certain directions. Hence, the decision support system of the Anthropocene relies on results of complex system models and requires pro-active governing, because the system is typically slow to respond.

If one connects these discourses on modeling to a wider social perspective, one might view these simulations of the planet as the next stage in cartography. Cartographers known from history mapped distant lands and thereby practically handed these lands to their rulers. In contrast, ‘Earth system’ scientists produce ‘images’ of possible, distant futures, whereby they enable decision-makers to act at a distance and to strategically colonialize people living not in distant lands but in distant futures. If this appears to be an overestimation of ‘Earth system,’ it may be pointed out that with an Anthropocene understanding of the time lags in the ‘Earth System,’ the use of natural resources such as fossil fuel may be aimed at wellbeing in the present at the calculable expense of people in distant places as well as futures. However, this knowledge should not be considered to be working only one way, as it may also be used to motivate our responsibilities for future generations, their privileges and free decision-taking. From a different angle, the colonialization of future populations is already on-going through the present use of resources; what the ‘Earth System’ models do is to make the effects calculable and visible.

In conclusion: Based on an experience partly produced by ‘Earth system’ modeling, the major funders of research on global environmental change expect to soon have a seamless and holistic decision support system to manage a transition to global sustainability. Almost thirty years of ‘Earth system’ science has produced a view of our times as the Anthropocene (Steffen et al. 2011). More than that, however, the discourses on modeling connected to GAIM and AIMES have produced confidence in the ability to integrate components into seamless models. Policy makers dealing with sustainable development and the global environment may dream of the “one model to fit all”, i.e. a model that provides them with all the answers they need regarding the effects of policies in times of global change. Drawing on Edwards’ (2001) argument that modeling is a process of world-building, a world governed by an “Earth System Analysis and Prediction System” rests entirely on the confidence in a universal

formalism which is only endorsed by a part of the research community on global environmental change.

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