Global Modelling: Managing Uncertainty, Complexity and Incomplete Information

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Abstract

Human activities change the environment on a global level. Global modelling is used to derive insights in the interactions between humans and their environment. However, the possibility to validate those global models is limited. In fact, too little information is available, many subjective assumptions are made and a single model cannot cover all relevant scale levels and processes. These limitations already appeared in the early seventies. Current global modelling activities still deal with the same dilemma's, often in the same way as the strongly criticised world models of the early seventies. We sketch some recent developments which can help to manage the persistent dilemma's. We focus on the use of different modelling paradigms and on the use of different world views to analyse the consequences of subjective assumptions to be made in global models.

keywords
global modelling, validation, complexity, uncertainty

1. Introduction

The history of humankind is a continuing record of interactions between peoples' efforts to improve their well-being and the environment's ability to sustain these endeavours. Environmental constraints led to innovations and social development, as well as social stagnation and human suffering. While the interactions throughout most of history were on a local scale, during the last decades mankind has become aware that the complexity and increasing scale of the interactions are demanding new forms of environmental management. People have become aware of various new threats for mankind, such as climate change, acid rain, ozone depletion, resource exhaustion, and limits to the availability of food and unpolluted fresh water. In fact, the globe is already changing rapidly due to human activities (Vitousek, 1997).

One response from the scientific community to the increased influence of human activities on its (global) environment is global modelling. Making accurate predictions for long term future developments is inherently impossible. However, models can help us to show the interdependence of the various activities and consequences in time and space. In that way models can be used to communicate information and insights from the scientific community to policy makers and stake-holders. A recent development in the efforts to support policy-making and to stimulate the science-policy dialogue, is the development of integrated assessment models (IAMs). These models integrate simplified versions of expert models into one framework. Integrated assessment models have been used to support acid rain policy (e.g. Alcamo *et al.*, 1990) to address the climate change problem (e.g. Rotmans, 1990, Alcamo, 1994, Nordhaus, 1994) and global change (e.g. Rotmans and de Vries, 1997).

Current projects in integrated assessment modelling elaborate on a tradition that was founded in the early 1970's by the Club of Rome (Forrester, 1971; Meadows *et al.*, 1972, 1974). Over the past

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20 years, numerous global models have been built in the tradition of system dynamics (Brecke, 1993). Those models were useful for their qualitative, rather than quantitative results. But the criticism on the validity and incompleteness of the models in scientific circles made this approach never get into the scientific mainstream. The world models were found to be based on too little empirical data, have a too high aggregation level and include many subjective assumptions of the model builders. Risbey *et al.* (1996) wonder if the current generation of integrated assessment modellers ignore the parallels between world models of the early 1970's and the current stream of integrated assessment models as the world models were so heavily discredited.

In this paper we address the validity issue of global models. We argue that the critique on the earlier world models still holds for the current activities in integrated assessment modelling. However, there are various approaches to deal with the critique. Some approaches to manage uncertainty, complexity and incomplete information are discussed in this paper.

2. The World Models

The first generation of world models used the system dynamics approach as developed by Forrester. According to the system dynamics approach, the world can be described by a conglomeration of interacting feedback loops. Originally, Forrester developed system dynamics as a means of helping to solve management problems in industrial firms (Forrester, 1961; 1969), but he claimed that system dynamics can be applied to any kind of system, industrial, political or social. In June 1970, Forrester gave a presentation of his system dynamics scheme at a meeting of the Club of Rome. A sketch of the world system resulting from the interactions with the Club of Rome was published in 1971 (Forrester, 1971). In the meantime resources became available for a larger project which resulted in the book Limits to Growth (Meadows *et al.*, 1972).

The World 3 model of Meadows et al. used Forrester's model, World 2, as a prototype. They elaborated the world model and estimated many relations from empirical data which was not done for the World 2 model. The World 3 model contains the sectors resources, population, pollution, capital and agriculture on an aggregate global level. The "standard run" of the World models is one of growth followed by collapse (Figure 1). The collapse occurs because of non-renewable depletion. The industrial capital stock grows to a level that requires enormous input of resources, more and more capital must be used to obtain those resources, leading to less re-investments and finally collapse of the industrial base. Population decreases when the death rate is driven upward by lack of food and health services.

Although it was recognised that there are various shortcoming in the model, Meadows *et al.* say:

We feel that the model described here is already sufficiently developed to be of some use to decision makers. Furthermore, the basic behaviour modes we have already observed in this model appear to be so fundamental and general that we do not expect our broad conclusions to be substantially altered by further revisions (Meadows *et al.*,1972, page 22).

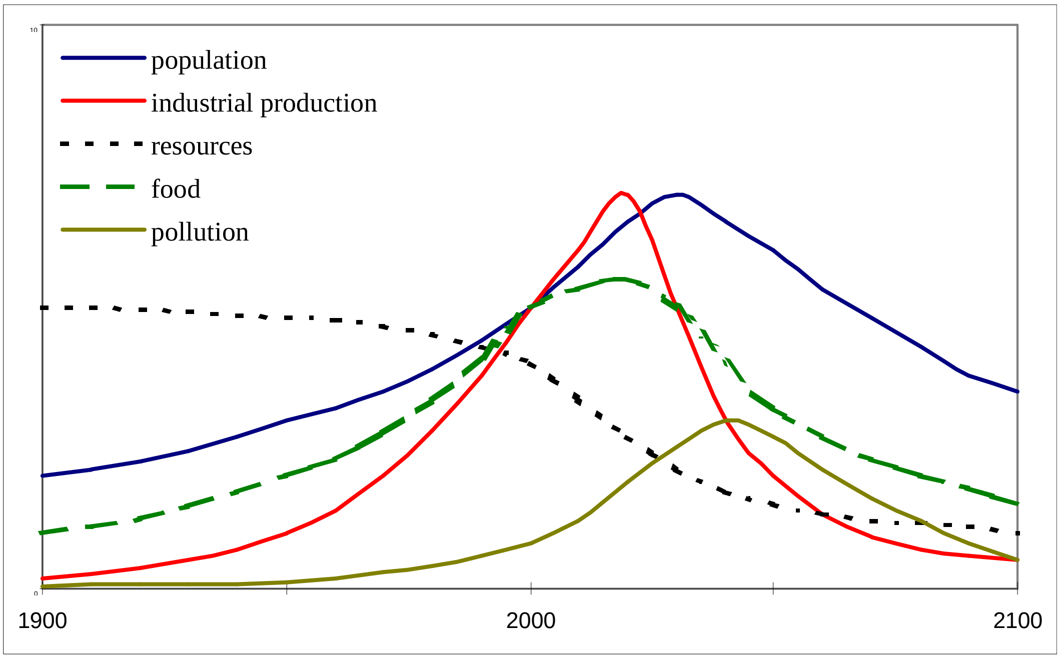

Figure 1. Standard run of World 3

The publications of the World 2 and 3 models coincided with the increasing interest in environmental degradation due to human activities. The report had a large impact on the public debate.

It also received a lot of critique. Nordhaus (1973), for example, classified the approach of Forrester and colleagues as misleading while, according to him, it was not enough empirically tested and did not fit within the mainstream economic approaches. The Science Policy Research Unit of the University of Sussex carried out a project to analyse the world models (Cole *et al.*, 1973). Their main conclusion was that due to the scarcity of relevant empirical information, relationships in the world models are subjective. Given the uncertainties, other sets of equally plausible assumptions can lead to a complete different picture of the future. In fact, a parameterization of the model can be derived which lets the industrial output, resource use and pollution grow without limits. The Sussex group argues that the outcomes of the models are largely the mental models of the researchers: Malthus in, Malthus out[2].

If we gather the critique on these world models, three categories can be distinguished:

- Uncertainty: incomplete knowledge about processes leads to subjective assumptions on relations like pollution affecting health and economic growth lowering birth rate. Moreover, subjective assumptions are made on e.g. technological developments and the availability of natural resources.
- Complexity: To manage the complexity of changes at different scale levels the world models are aggregated into a single region which is too aggregated to be useful for policy makers. Moreover, there are essential differences between regions which makes a lower aggregation level necessary.
- Incomplete Information: The available empirical information is too scarce to calibrate or validate the models according to scientific standards.

[2] Almost two centuries ago economist Thomas Malthus saw food production as a land-limited resource that could not possibly be increased quickly enough to keep pace with a growing population.

3. Integrated Assessment Modelling

Due to the strong criticism on the early world models, global modelling did not became a main-stream scientific activity although various other global models were made in response to the early ones. These new models try to use different techniques and aggregation levels (Meadows, 1985).

Recently, a new approach to global change has emerged: Integrated Assessment. It is felt that this approach could help prioritise policy making and research activities and get insight in uncertainties and missing links of knowledge. It is used in a process whereby knowledge from a variety of scientific disciplines is combined, interpreted and communicated, with various stakeholders such as scientists, policy makers and NGO's involved. This complex, intuitive, and value-loaded process cannot be performed with a single method; diverse approaches are needed, such as integrated assessment models, policy exercises, dialogues between science and policy, data analysis, scenario-analysis and expert models. This may increase the robustness of insights and conclusions of the assessments.

The generation of models currently known as integrated assessment models started with focus on the acid rain issue. The RAINS model (Alcamo *et al.*, 1990), which was developed and used to address the contentious issue of acid rain in Europe, was one of the more successful among these earlier studies. More recently, the challenge of global climate change has prompted the development of models such as the IMAGE model (Rotmans, 1990; Alcamo, 1994); the DICE model (Nordhaus, 1992); the MERGE model (Manne *et al.* 1994) the PAGE model (Hope *et al.*, 1993); ICAM (Dowlatabadi and Morgan, 1993) and TARGETS (Rotmans and de Vries, 1997).

In general, integrated assessment models try to describe quantitatively as much as possible of the cause-effect relationship and the cross-linkages and interactions between the elements of the system. More specifically, integrated assessment models of global change are designed to analyse this phenomenon from a synoptic perspective. Although there are some serious attempts being made to construct an integrated model of the Earth's atmosphere, hydrosphere, and terrestrial biosphere (Fisher, 1988; Krapivin, 1993), it is conceptually and technically not yet possible to link, let alone integrate, a variety of complex, detailed and three-dimensional models. Therefore, it is often more appealing to make use of reduced versions for each component of the integrated assessment framework, which are small enough to be comprehensible, flexible, and easily linked to one another. A metamodel is a simplified, condensed version of a more complicated and detailed model (expert model), which provides approximately the same behaviour as the expert model from which it is extracted. There are various methods for developing metamodels, which vary in complexity, ranging from fully parameterized models to process-oriented models. A manageable approach is then to use the core knowledge of the various expert fields in an integrated framework. Interlinking the resulting metamodels requires the definition of one single conceptual framework, so that harmonisation can be obtained with respect to aggregation level, temporal, and spatial scales.

However, this approach still faces the same problems as the world models of 25 years ago:

- There is much uncertainty on various basic relationships. Therefore, the assumed relationships can not be validated objectively.
- The different scales which are used in integrated assessment models are subject to discussion: a high aggregation level makes it of less use for policy making and more difficult to validate against more disaggregated expert models; a disaggregated model is more difficult to manage and may give a false impression of accuracy.
- Whatever the aggregation level, there are not enough empirical data to calibrate models satisfactory, let alone to validate the models.

Despite these problems we want to address the validity of these models. Given the difficulties we first will discuss the kind of validation one might expect.

4. Are Integrated Assessment Models valid images of reality?

Validation can be subdivided into two different types. The first is practical validation, which concerns the outcomes of the model as compared to observational data. The major difference with calibration is that the comparison should be based on a new set of data, which lies outside the calibration pathway. Wherever possible, independent data sets and observations are used to validate components of integrated assessment models. However, all the available data may already be needed for calibration of the models, so this kind of validation is rather limited for integrated assessment models. In fact, we can only perform one experiment to test the integrated global model: reality itself.

The second type of validation is conceptual validation, to test whether the model represents the real system. This implies that the internal structure of the model is tested, i.e. whether the concepts and theoretical laws of the system under consideration are interpreted and represented in a sound way.

Because our empirical record of processes on the global scale is far from complete and by definition only one experiment can be done, validation of a world model by empirical data is a mission impossible. Moreover, the large uncertainties make it possible to construct various plausible but contradictory explanations about phenomena. For example, the missing carbon sink, which is the amount of carbon which is taken up from the atmosphere by the terrestrial biosphere and/or the oceans is a highly uncertain quantity which allows to various descriptions with different results (Schimel *et al.*, 1995), and different policy recommendations. Another striking example is the discussion about the timing of climate change policies. According to the bottom-up engineering studies there are many opportunities to cut the emissions at zero or negative costs, while the top-down macro-economic analyses find that every additional policy to reduce emissions compared to a no-policy reference case will cost up to various percentages of the GNP (Grubb, 1996).

Validation of global models seems to be an activity full of value-loaded judgements. We argue that validation of global models should make this aspect of global modelling transparent and explicit. We use the following framework to work out this statement.

5. A Framework of interacting levels of model reality

By integration one should bridge what is usually referred to as domains of natural and social sciences. A useful approach is to distinguish three levels of complexity which differ with respect to the degrees of freedom of the system elements and, partly as a consequence of this, with respect to the nature of our knowledge about them (De Vries, 1994; Figure 2). The relevance of distinguishing these three levels is that it allows an explicit discussion of the concepts and methods used in integrated assessment, and their differences.

The first level consists of physical reservoirs and flows which correspond partially to observable reality. Model variables, at this level, usually have an explicit and formal correspondence with real world observable phenomena. At least in principle, the laws of physical, chemical and biological science hold, e.g. conservation of mass and energy. The next level maps the behavioural and informational structures which govern human interference in the underlying physical environment. Such behaviour is described by information-dependent sets of rules. The rules describe actors, varying from individuals to multinational companies and institutions. Models of actors are usually meta-relationships based on correlation analysis of a limited sample of data. The third level comprises values, beliefs and ideas that reflect and rationalise people's behaviour. Policy issues arise at the highest level, so that at this level the design of macro-oriented policies enters the scene. Generally speaking, this level is merely included in models in the form of response variables chosen *ex ante*. The normative dimension and decision-making processes, also at this level, are not - and mostly cannot be - included in quantitative models. We need to search for complementary methods to address those aspects and nuances of human values.

These three levels of complexity are of course only a simplified representation of a continuous spectrum. Its use, however, may help to communicate that ‘strong’ science, generating statements on the basis of controlled experiments, only covers a limited domain of the physical environment and an even smaller part of the levels of behaviour and values. Many of the controversial issues related to global change, for example, are rooted in limited understanding or ignorance about certain physical phenomena. This gives rise to quite distinct interpretations of observations about the physical environment, thereby supporting conflicting models of how this part of the world functions. Such uncertainties may be resolved as science proceeds. However, there will always be competing explanations of real-world observations which in turn can be used to support one’s behaviour and one’s beliefs, values and preferences, especially at higher levels of complexity.

Another facet of this complexity axis is that it allows an explicit discussion of the concepts and methods - as well as their differences - used in the natural sciences and in the social sciences. The former use the techniques of differential and integral calculus to describe physical and chemical processes in environmental compartments, but they also have to deal with uncertainties as soon as the applications are outside the realm of controlled experiments, The latter are used to large uncertainties in describing (human) behaviour and have often employed models from the physical sciences as analogues for the construction of hypothesis (De Vries, 1989). The science of ecology is somewhere in between the first and the second level of Figure 2 which has given it a great heuristic role in modelling global change (Clark and Holling, 1985). In the last decades, the search for new methods and approaches to bridge the gap has intensified. System dynamics, applied general equilibrium and actor-oriented models, cellular automata and genetic algorithms are some of the tools that have been applied more recently.

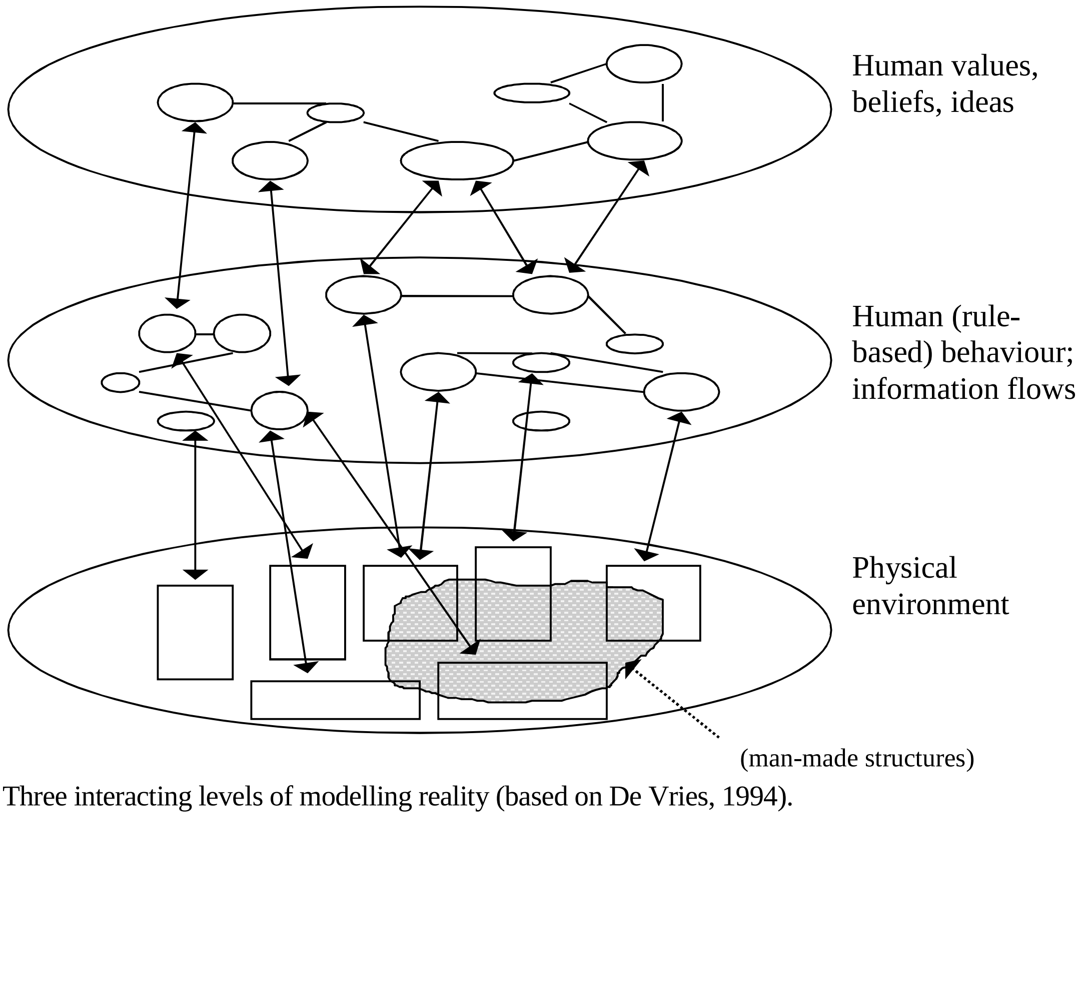

Figure 2. Three interacting levels of modelling reality (based on De Vries, 1994).

Summarised, we can at least distinguish two aspects of the construction and validation problem of global models. Firstly, global models integrate various parts of reality into one framework. This process is an interdisciplinary activity where mainly economics and natural science interact with each other. We will analyse how successful this integration of disciplines is in some current integrated assessment models. Secondly, we will have a close look at the subjectivity of assumptions. Often there are different plausible explanations which can explain our incomplete knowledge of reality. Therefore, we may cluster assumptions within the model according to different world views in order to construct different plausible explanations of the past and plausible long-term scenario's for the future.

5. Integration in Modelling Global Change

As was discussed in Section 3, global modelling re-emerged during the early 90's as integrated assessment modelling, partly because of the importance of the global climate change problem. We will use this problem to address the question whether global models do really integrate knowledge from different disciplines.

Although it was known for more than a century that the increasing use of fossil fuels may lead to global warming, it took until the mid 80s before an international scientific consensus has developed on the issue of anthropogenic climate change as a serious problem. The problem of climate change rapidly moved to the political agenda. In 1987 the Intergovernmental Panel on Climate Change (IPCC) was established to assess the issue of climate change and to report this information to the governments. The IPCC is nowadays seen as the organisation which co-ordinates an integrated assessment of global climate change. This assessment is mainly based on modelling studies, varying from expert models up to integrated assessment models.

The IPCC established in 1988 three working groups. The first was asked to assess available scientific evidence on climate change; the second was to assess available environmental and socio-economic impacts of climate change. The third was to formulate response strategies. The three working groups published reports in 1990 and 1996 (IPCC, 1990;1996). The first working group was rather successful as they reported that it was highly certain that there is a human-induced climate change. The influence of this report stems from the fact that it was regarded as 'scientific' and hence detached from political bias, and from the series of abnormal climate events across the globe (Jäger and O'Riordan, 1996). According to Jäger and O'Riordan (1996), the other working groups have had less impact:

" The other working groups were far less successful, partly because it is undesirable to separate adjustment from impacts, and also to isolate analysis from policy prescriptions. The fact that the Russians chaired WG2 and the Americans chaired WG3 was also politically dictated, and virtually guaranteed that both groups would be ineffective in informing the all important negotiation process. It is also a sad reflection on the state of the social sciences at present, that their practitioners cannot produce a coherent view of what causes climate change in terms of human needs and wants and associated economic and technological 'drivers', what should be done about these, and what would be the social, political and economic consequences. Compared with the consensus-oriented format of the natural scientists, the social scientists have behaved in a more disorganized and non-credible manner."

This shows that the IPCC itself meets the difficulties to deal with the three levels of complexity. The first level, the physical system was successfully assessed. Although there are still many uncertainties in the functioning of the climate system, and although there are still too little observations to measure with certainty the antropogenic contribution to a possible observed climate change, the assessment of the physical level could be performed fairly successfully because of the formal laws in natural science and the correspondence of the hypotheses with the observable data.

The second and the third level of complexity were less successfully assessed. Observational data are less easily derived at these levels. For example, how will economic development be affected by a climate change or by measures to avoid emissions of greenhouse gases? The information needed to feed the models at these levels of complexity are derived by interpretation of different types of data. This interpretation can be largely influenced by subjective bias - world view - of the scientists. What actually emerged in the working group 2 and 3 is a neo-classical economic approach to deal with the assessment of the impact of climate change, hence the costs of climate change, and to provide response strategies, hence cost-benefit strategies. However, many other approaches from social science to assess the impact and response strategies, such as political science, ethics, technology assessment, ecological economics and so on, were consequently less visible in the assessments of the IPCC. A probable explanation of the dominance of the neo-classical economic approach is its strong mathematical 'scientific' approach. Nevertheless, the model dominated IPCC assessment led to two streams in global modelling: one which is rooted in natural science and one which is rooted in neo-classical economics. Unfortunately, these approaches are not always consistent with each other. In order to illustrate this conflict we use the following two "cartoons".
The neo-classical economic model can be characterised by the following description (Figure 3). Given is a rationally behaving agent who maximises its discounted sum of consumption for the coming 100 or more years. Decisions will be made on how much to consume and re-invested, and how much emissions will be reduced at costs will slowing economic growth. On the other hand climate change may also lead to a reduction of income in the longer term. Economists formulate integrated problem as an optimisation problem of scarce resources. In order to derive the mathematical optimum one often simplifies the description of the system. A consequence of such a simplification might be the incorrectness of the resulting description of the natural system.

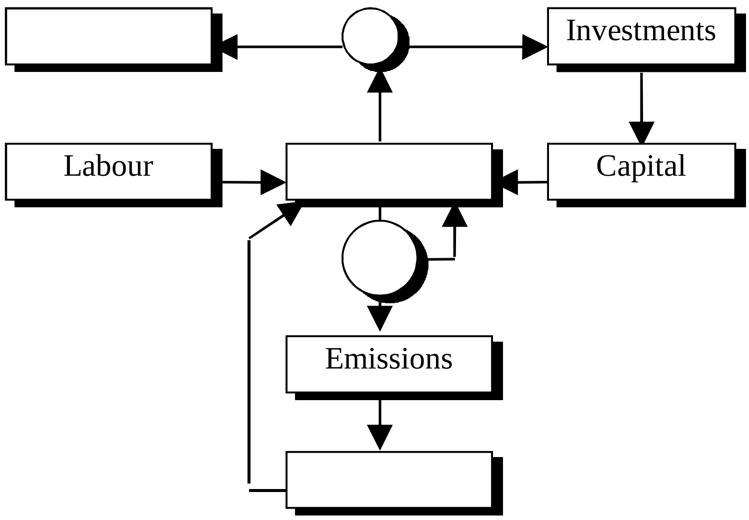

Figure 3: An integrated model from the perspective of economics

The natural scientific model can be characterised as a simulation of the consequences of human activities (Figure 4). Given the emissions of greenhouse gases and possible other activities such as land use changes, the changes of the natural system in the various components is simulated by rather complex models. Although it uses a more reliable description of the natural system, it does not take into account the consequences of a climate change on human activities nor the dynamics behind the activities e.g. prices.

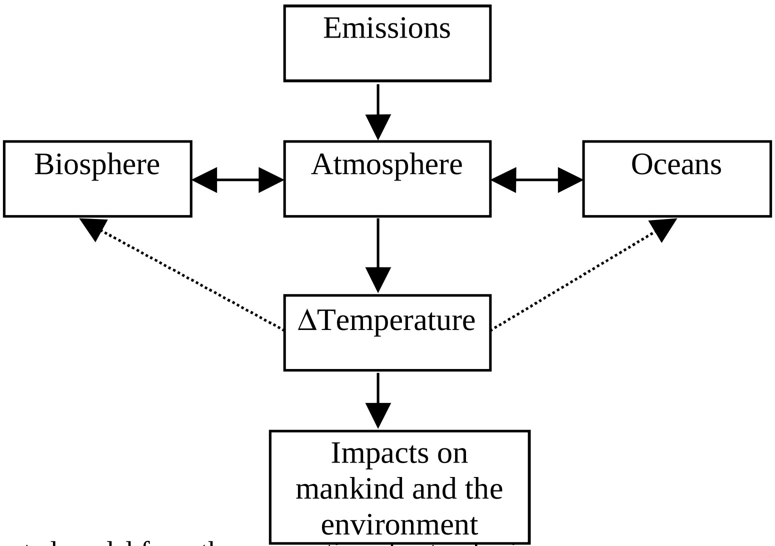

Figure 4: An integrated model from the perspective of natural science.

An overview of prominent models in the field of integrated assessment modelling of climate change is given in Table 1. It clearly shows the main differences between the approaches: the level of detail and the treatment of decision making.

Table 1: Summary characterisation of integrated assessment models (based on Rotmans and Dowlatabadi, 1998)

Model	A	B	C	D	E	F	G
Economics							
DICE	0,1	0	1	1	0	1	0
RICE	0,1	0,1	1	1	0	1	0
CETA	0	0,1	1,2	1	0	1	0
MERGE 2	0,1	1	1,2	1	0	1	0
Natural Science							
IMAGE 1	0,1,3	0	0,2,3	1	1	1	1
TARGETS 1	0,1,2,3,4	0	1,2,3,4	1	1,2,3,4	2	1,2
IMAGE 2	0,1,2,3	3	0,2,3	3	1,2,3	1	1
MiniCAM	0,1,2,3	2,3	1,2,3	3	0	1	1
GCAM	0,1,2,3	2,3	1,2,3,4	3	0,2	1	1

Notes
A: Forcings: 0 = CO_2; 1 = other GHG; 2 = aerosols; 3 = land use; 4 = other
B: Geographic Specificity:0 = global; 1 = continental; 2 = countries; 3 = grids/basins
C: Socio-economic dynamics:0 = exogenous; 1 = economics; 2 = tech choice; 3 = land use; 4 = demographic
D: Geophysical simulation: 0 = ΔF; 1 = Global ΔT; 2 = 1-D ΔT, ΔP; 3 = 2-D ΔT, ΔP
E: Impact Assessment:0 = ΔT indexed; 1 = sea level rise; 2 = agriculture; 3 = ecosystems; 4 = health
F: Treatment of uncertainty: 0 = none; 1 = basic; 2 = advanced
G: Treatment of decision-making: 0 = optimization; 1 = simulation; 2 = simulation with adaptive decisions

An integrated approach of integrated modelling might be the combination of the two different approaches. The advantage would be that it would combine the strong points of each approach although one should overcome the differences of scale and modelling paradigms.

To be more specific about this difference we briefly describe two well known and widely used models: the DICE model of the economist Nordhaus and the IMAGE model of the Dutch National Institute of Public Health and the Environment (RIVM).

- **DICE** (Dynamic Integrated model of Climate and the Economy) (Nordhaus, 1994) is an optimisation model of the energy-climate interaction based on aspects of optimal growth theory. DICE calculates optimal capital accumulation as well as greenhouse gas emission reduction by maximising the discounted value of utility from consumption. DICE envisages the world economy as producing a composite commodity associated with an initial stock of capital, labour, and level of technology. Output is represented by a standard, constant-return-to-scale Cobb-Douglas production function in capital, labour and technology. Climate change may lead to damage costs which reduce the growth of the economic output. On the other hand, reduction of emissions which cause climate change, may reduce the growth of economic output. Population growth and technological change are regarded as being exogenous, while the optimised flow of consumption over time determines accumulation of capital. Only one actor, the global commoner, rules the world. This actor has perfect knowledge of the system and optimises his discounted utility of consumption. In a regional version of DICE, the RICE model (Nordhaus and Yang, 1995), game theory is used to determine the (non) co-operative optima.
- **IMAGE 2** (an Integrated Model to Assess the Greenhouse Effect) (Alcamo, 1994) is a multi-disciplinary, integrated model to simulate the dynamics of the global-biosphere-climate system (Figure 5). The objectives of the model are to investigate linkages and feedbacks in the system and to evaluate the consequences of climate-related policies. Dynamic calculations are performed from 1970 to 2100, with a spatial scale ranging from grid (0.5^o x 0.5^o latitude-longitude) to world regional level, depending on the submodel. The model consists of three fully linked subsystems: Energy-Industry, Terrestrial Environment, and Atmosphere-Ocean. The Energy-Industry models compute the emissions of greenhouse gases in 13 world regions as a function of energy consumption and industrial production. End-use energy consumption is computed using various economic/demographic (exogenous) driving forces. Each sector is assumed to consume a certain amount of energy associated with indicators like industrial and service value added or GNP per capita. The energy demand can change due to autonomous and price induced energy conservation. The activity levels, related to economic growth, are scenario dependent. Fuel use depends on fuel prices and technical constraints. The Terrestrial Environment models simulate changes in global land cover on a grid scale based on climatic and economic factors, as well as on the flux of CO_2 and other greenhouse gases between the biosphere and atmosphere. The changes in land use are determined by the suitability of the land and climate and the regional demand for food. The Atmosphere-Ocean models compute the build-up of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns.

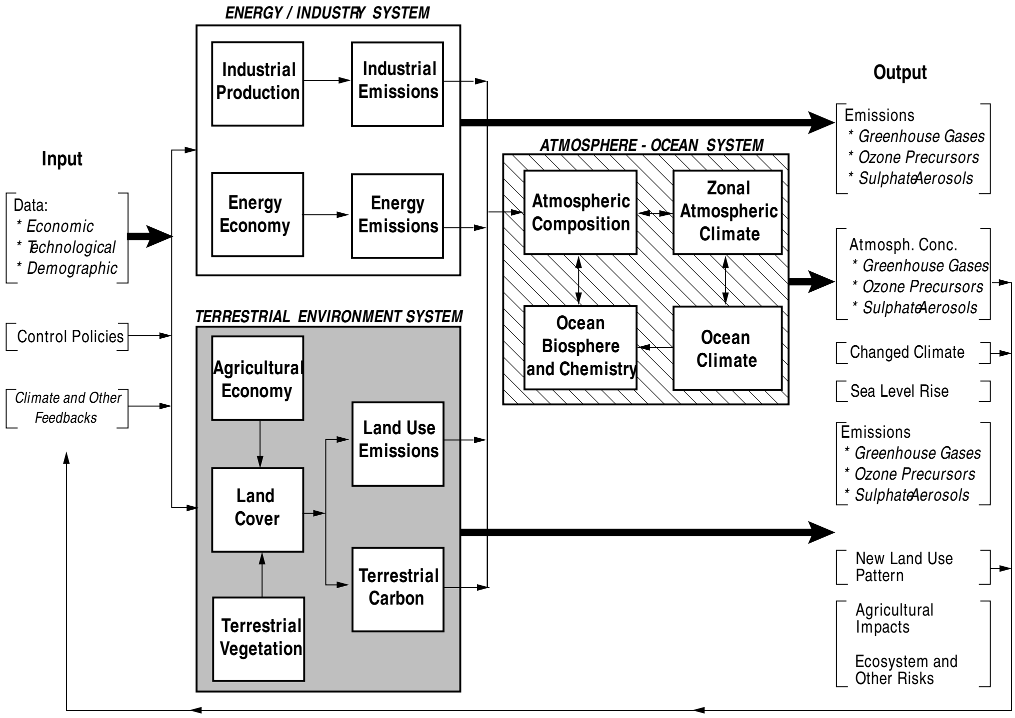

Figure 5: IMAGE 2 - Framework of models and linkages.

A possible integration of the two approaches would conceptually look like Figure 6 where Figure 3 and 4 are combined. This leads to a complex optimisation model which probably not be solved by tradition techniques.

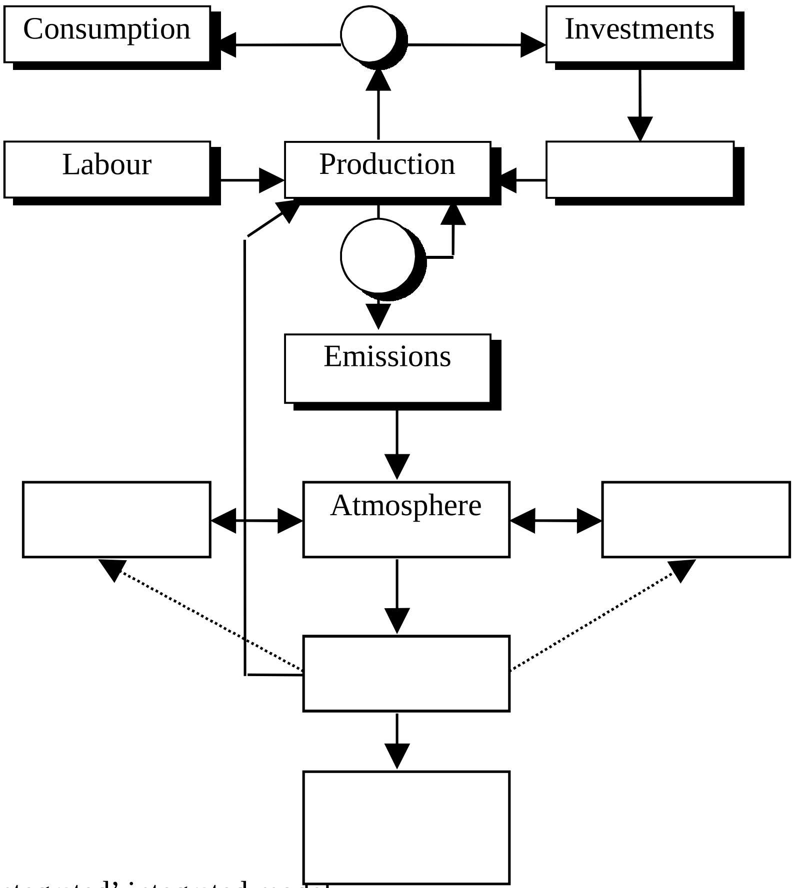

Figure 6: An 'integrated' integrated model.

Janssen (1997, 1998) has worked out this conceptual approach and has constructed a coupled model (OMEGA), of the DICE model and the mathematical system version of IMAGE 1 (Braddock *et al.*, 1994). The aim of Janssen's study was to assess the consequences of the simple description of the natural system in the DICE model. Various other papers have assessed the limitations of the DICE model by critiquing the inadequate description of the climate system (Price, 1995; Fiddaman, 1996; Kauffman, 1997; Schultz and Kasting, 1997). but Janssen (1997, 1998), and also Fiddaman (1996), provide alternative approaches to integrate economics and climate change.

By substituting the IMAGE model for the three equation description of the environment in the original DICE model, Janssen derived a complex optimisation model which was successfully be solved by different optimisation routines. A typical example which illustrates the consequences of differences in describing the climate system is the following, Suppose a policy target is formulated as the stabilisation of the CO_2 concentration at a level of 400 ppmv[3]. A number of experiments have been conducted in which the starting year of mitigation is varied, using the starting years 1990, 2000, 2010 and 2020. Using the OMEGA model, the results suggest that a delay until 2010 may lead to a drastic reduction in order to avoid exceeding 400 ppmv (Figure 7a). If policy follows the

[3] The current level is 360 ppmv, and the expected level in 2100 if no additional climate policy is implemented is about 700 ppmv.

reference scenario until 2030, the concentration will exceed the target level for about two decades. In case DICE is used, the required reductions are more drastic (Figure 7b), and the CO_2 concentration level exceeds the 400 ppmv concentration targets, of the enhanced mitigation policy is not implemented before 2020 (Figure 7b). The results also show that similar emission paths lead to quite different concentration levels.

The explanation for this difference mainly deals with the constant parameters in the carbon cycles equation of the DICE model. It is expected that the carbon flow between ocean, atmosphere and biosphere changes with changing atmospheric CO_2 concentrations. While the parameters in the DICE model are estimated on historical measurements, the derived equation is only valid for a limited amount of possible scenarios. In fact, DICE is only able to estimate future concentrations by extrapolating historical behaviour. These constant carbon flows are not valid according to our present knowledge about the carbon cycle, and in that way the DICE model is not a valid description of the climate change system as was also argued by Price (1995), Kauffman (1997) and Schultz and Kasting (1997). This means that the cost-benefit analysis of Nordhaus himself is based on a invalid description of the climate system. Actually, it are not the differences between the two experiments that matter. Ignoring the state-of-the-art knowledge of a significant part of the problem should lead to rejection of the model.

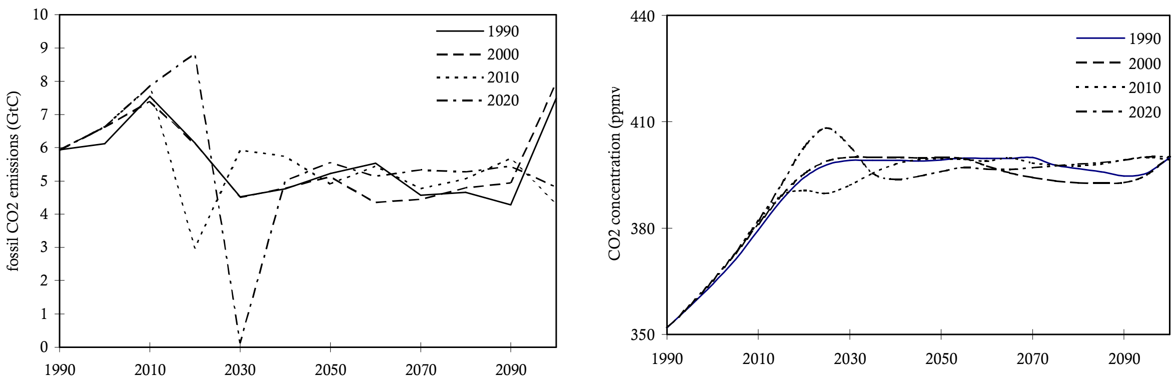

Figure 7a: Fossil CO_2 emissions for delayed response strategies starting in 1990, 2000, 2010 and 2020 using the OMEGA model meeting the 400 ppmv target, and the resulting CO_2 concentrations.

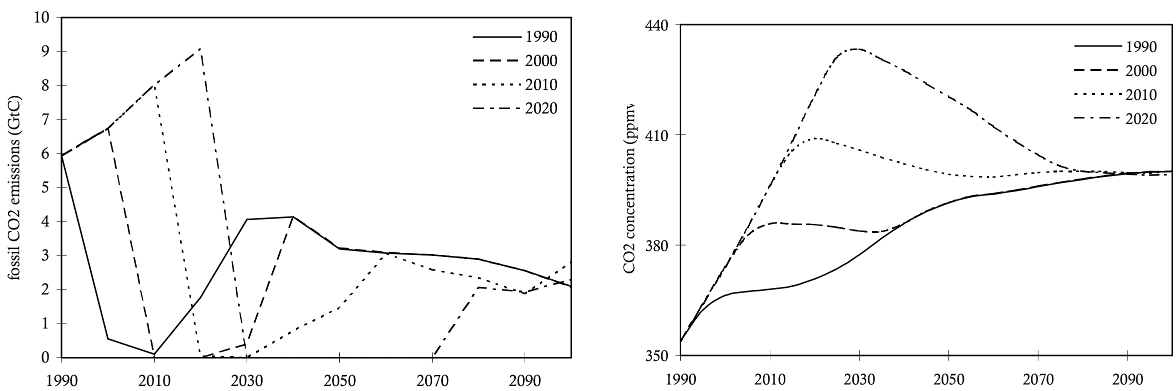

Figure 7b: Fossil CO_2 emissions for delayed response strategies starting in 1990, 2000, 2010 and 2020 using the DICE model meeting the 400 ppmv target, and the resulting CO_2 concentrations.

The optimization approach with the OMEGA model were in review discussions with economists not accepted as an alternative to the DICE model. Natural scientists favour the analyses with the model to show the consequences of including a more realistic climate model. However, they prefer

a simulation approach where they can more easily analyse the consequences of human activities in a detailed way. The economists do not see the relevance of including a complex climate system while it leads not to significant different conclusions for cost-benefit scenarios. That the results as presented in Figure 7 differ significantly does not matter while it is found obvious that another description of the climate system leads to other results. Furthermore, they prefer a simple mathematical model in order to be sure of the mathematical optimality of the solutions.
Although the classification between economists and natural scientists is a rather artificial one, this case study illustrates that one integrated global model might not be the holy grail where we are looking for. The early world model builders also recognised the limitations of building one model of everything. Forrester (1985) wrote in a memo in 1971 that the integrated model itself is not the main aim of the model builders:

In fact, for any particular real-life implementation we can expect that there will be a series of models simultaneously existing and simultaneously in evolution. Different model will address themselves to different issues. The various issues will evolve and become clearer. New issues will arise which require a new model, or combinations of models which previously had existed separately.
Rather than stressing the single-model concept, it appears that we should stress the process of modeling as a continuing companion to, and tool for, the improvement of judgement and human decision making.

The dilemma of integrating the various disciplines into one framework is currently recognised by a number of groups in the field of global modelling. Instead of building one integrated model a number of groups develop an integrated framework of different types of models. This means that assumptions, scenario descriptions and in- and outputs are linked between the models, but the models themselves keep their special characteristics. Often such a framework is developed as a co-operation between various institutes, or various departments within one institute. Examples of such activities can be found at MIT (Cambridge, USA), the RIVM (Bilthoven, the Netherlands) , Battelle Institute (Washington, USA) and IIASA (Laxenburg, Austria). For example, instead of integrating a world economic model, the IMAGE team closely work together with the Dutch Bureau for Economic Analysis (CPB) who developed the World SCAN model, a regionalised world model for economic analysis. Joint scenario construction is found to be more fruitful and derive more credibility instead of building it all into one model and losing the special characteristics of both the models.

7 World Views

Uncertainty is often viewed as a statistical artefact, although it can and should partly be traced to different interpretations of reality. As noticed before, Cole *et al.* (1973) analysed the World 2 and 3 models and conclude that they are able to derive totally different conclusions if they change some parameters and relationships of the world models which may be equally plausible given the scarce amount of data and scientific understanding of important phenomena. It is therefore crucial to acknowledge different interpretations of reality when one build models of issues wrapped with large uncertainties. Therefore, it is increasingly common to use different perspectives or world views in discussions on sustainable development to derive consistent qualitative and quantitative projections (e.g. De Vries, 1989; Rayner, 1991; Schwartz and Thompson, 1990; Thompson *et al.*, 1990; Colby, 1991; WRR, 1994).
Computer models are mathematical representations of the mental model of the model builders. Because of the large uncertainties in global modelling it is to be expected that subjectivity, in the

form of different mental models, can play a crucial role in the results of the modelling studies. A quantitative application of world views is worked out by the Global Dynamics and Sustainable Development group of the RIVM (Janssen and Rotmans, 1995; Van Asselt and Rotmans, 1996; Rotmans and de Vries 1997; Janssen and de Vries, 1998). The cultural theory of Michael Thompson and colleagues (1990) is used to derive a scheme of different world views. Cultural Theory can be used to describe the differences in behaviour of actors which is nicely illustrated by the following example on the Brent Spar:
If there were only markets and hierarchies then the solution that was agreed between Shell (the market actor) and the British Government (the hierarchical actor) would have come to pass, and the Brent Spar would now be mouldering in its watery grave. It isn't: it is sitting bolt-upright in a Norwegian fjord. Greenpeace - an actor from a third kind of solidarity (we call it egalitarianism) - winged its way in, literally and totally transformed the outcome. (Thompson, 1997)

The three 'active' perspectives from Cultural Theory - the Hierarchist, the Egalitarian and the Individualist - can be integrated as the corners of a triangle.
- Hierarchists believe that humans are born sinful, but can nevertheless be redeemed by virtuous institutions. Nature is stable in most circumstances, but can collapse if it crosses the limits of capacity. Therefore control is advocated as management style.
- Egalitarians believe that human beings are born good but also highly malleable by evil institutions. nature is highly unstable, and the least human intervention may lead to complete collapse. A preventive management style is preferred.
- Individualists believe that humans are self-seeking and unmalleable. Nature provides an abundance of resources and is believed to remain stable under human interventions. An adaptive management style is advocated.

Of course, in the real world, actors rarely express their views in such a caricatural way. They are in constant interaction and often have strategic and public relations in mind as well. Moreover, positions may be implausible or even inconsistent when stakeholders share only part of the underlying values and judgments. Nevertheless, this framework is found to be useful to be applied in a global modelling framework. The basic idea is that a set of heterogeneous agents have all their own world view and preferred management style (Table 2). We suppose that those world views may change if the agents are confronted with a persistent pattern of surprises. If agents change their world view, they are assumed to change their preferred management style as well. In this way, one may simulate a kind of learning mechanism on the side of the actors.

	individualist	**hierarchist**	**egalitarian**
world view			
idea of nature	skill-controlled cornucopia	isomorphic nature	accountable
myth of nature	natural benign	nature perverse/tolerant	nature ephemeral
concept of human nature	self-seeking	sinful	born good, malleable
management style			
driving force	growth	stability	equity and equality
type of management	adaptive	control	preventive
attitude to nature	laissez-faire	regulatory	attentive
attitude towards humans	channel rather than change	restrict behaviour	change social environment
attitude to needs/resources	expand resource base	rational allocation of resources	need-reducing strategy
economic growth	preferred: aim to create personal wealth	preferred: aim to avoid social collapse	not preferred
risk	risk-seeking	risk-accepting	risk-aversive

Table 2: Characteristics of Cultural Perspectives.

We have applied this framework to the problem of global climate change (Janssen and de Vries, 1998). A simple dynamic system is constructed which simulates the economy (investment decisions and the degree of emission reductions) and the climate system. By making different assumptions on climate sensitivity, technological development, mitigation and damage costs, three different possible worlds can be constructed. Suppose the agents have perfect knowledge and their world view fits exactly with the real functioning of the global system. In this hypothetical situation, so-called utopias can be constructed (Figure 8). In the utopia of the hierarchists, the economy grows at a stable rate of 1.5%/yr. The CO_2 emissions keep increasing in the short run, but the use of fossil fuels will be phased out in the longer run to avoid a dangerous level of temperature change. This policy leads to a stabilisation of temperature change. In the utopia of the individualists, economic growth is on average above 2%/yr. Due to limited efforts to reduce energy intensity, CO_2 emissions soar to over 40 GtC in 2100. However, the insensitive nature of the climate system leads to a temperature increase of only 0.5^{o}C. In the utopia of the egalitarians, economic growth is about 1%/yr which but CO_2 emissions are forced down by a strong policy on energy efficiency and a phase-out of fossil fuels in the early part of the next century. Nevertheless, global warming exceeds 1^o C because the climate system is assumed to be quite sensitive to human interference.

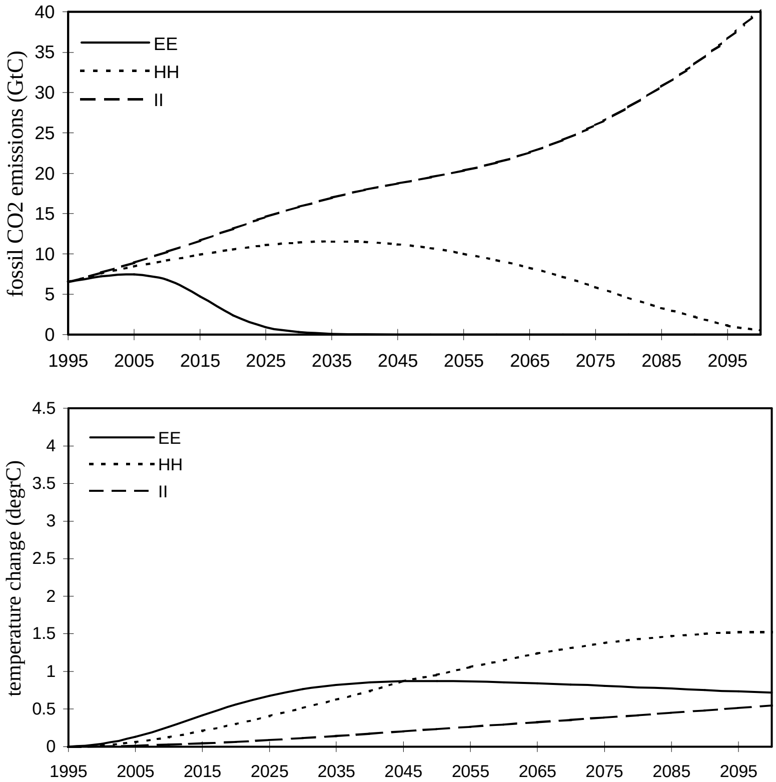

Figure 8: Projections of three utopias (Egalitarian (EE), Hierarchistic (HH) and Individualistic (II)).

If we include the more realistic assumption that agents do not have perfect knowledge and that their behaviour is biased by their world view, one is able to include, in a rough way, the possible adaptive response to climate change in the form of changing world views and hence changes in climate policy.

If is assumed that agents abandon their perspectives in the event of a surprise, that is, if observation differ from expectations, agents who adhere to a certain world view may switch to another one if it can better explain the observed behaviour of the system. Again three kind of experiments are performed, each with a different description of the global system. In each experiment agents start with a variety of possible world views. Agents change in time their world view, and therefore their management style which leads to emission pathways and temperature profiles as depicted in Figure 9. The expected emission profiles remain close to each other for a long time period. Not until the middle of the next century, the emission profiles begin to bifurcate. If a severe climate change is experienced, emission will decrease significantly but can not avoid a high temperature change of about 2.5^{o}C. In case the climate system is insensitive to antropogenic emissions, emissions increase sharply after 2040.

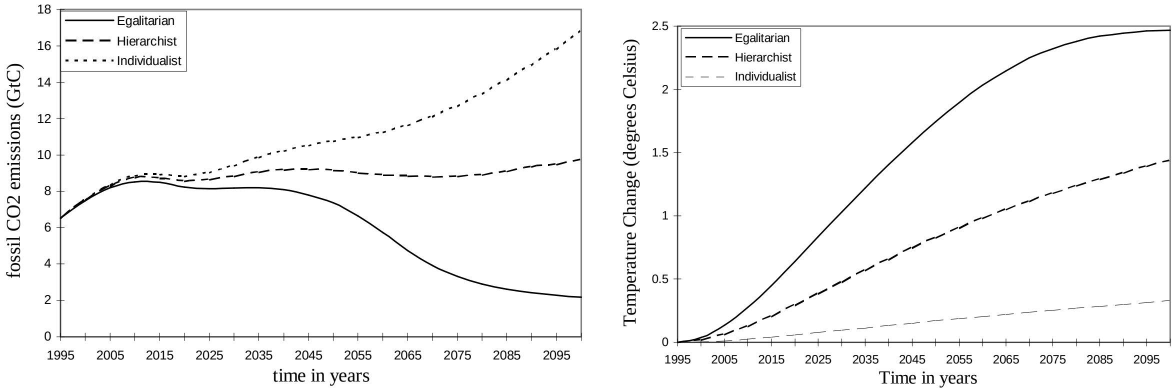

Figure 9: Average CO_2 emissions and temperature increases according to different views on the functioning of the global system

These quantitative thought experiments illustrate the consequences of assuming different views on the global system. The approach of adaptive agents might be a useful alternative to the agents with perfect knowledge (optimisation of control policies) and the agents without response (simulation of the impact of scenarios of human activities). Furthermore, it shows the importance of improving our understanding of social dynamics.

In the current[4] development of IPCC scenarios a more comprehensive approach is used than in former IPCC assessments. Those former IPCC scenarios (Leggett *et al.* 1992) were rather simple emission projections for different levels of economic and population growth (low, medium and high). The current development of emission scenarios are based on a number of storylines. Different possible socio-economic, cultural and technological developments are sketched such that four consistent stories are constructed. These qualitative stories will then be translated into different parameter values and relations within the computer models such that quantitative projections can be derived. After quantifying the qualitative story lines, a so-called open process will be started which enables other modelling groups of various parts of the world to criticise the work of the IPCC scenario group.

Such a ‘computer aided story-telling’ does include to some extent the diverging views and controversial evidence about the impact from greenhouse gas emissions. Yet, there are still important limitations in the IPCC scenario session such as the ignorance of a feedback of climate change on economic development, together with different possible descriptions of the environmental system.

8. Conclusions

Global models can be useful tools to assess the interactions between humans and their environment. They can be used to explore the consequences of possible socio-economic, demographic and technical developments on the state of the environment, and policies to reduce harmful impacts. In this way global modelling can be useful to support policy making with regard to sustainable development issues. However, global models have a rather poor quality in the context of formal validation of computer models: Not enough data are available to calibrate, let alone to validate the global models; large uncertainties in the information and scientific understanding leaves plenty of room for subjective assumptions; models are often too aggregate to confront the model with real life

[4] The authors are involved in this IPCC scenario development process.

data, and sometimes too detailed too acknowledge the limited understanding and information available. In fact, global modelling is confronted with the same dilemma's during the last 30 years, that is managing uncertainty, complexity and incomplete information. This paper do not give the ultimate solution to manage these issues successfully, but we have extracted a number of lessons from the past:

- It is the modelling process that matters, not the model itself.
- There is not one model of reality. Different models using alternative paradigms should be used.
- Explicit treatment of subjective assumptions is essential.

Global modelling, or integrated assessment modelling, is one key element of integrated assessment. The usefulness of models depends on the scientific quality of the models and the interactions between scientist and policy makers. We focused on the first issue and conclude that no objective judgement can be given on the quality of global modelling. However, explicit treatment and use of different modelling paradigms and perspectives is essential to derive insights in the diversity and complexity of global change. This insight can be of important use in decision making on shaping the future of mankind.

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