INTEGRATED ASSESSMENT MODELLING

Richard S.J. Tol[a,b,c]

[a] *Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany*

[b] *Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands*

[c] *Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA*

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1. Introduction

In the middle of the 1990s, integrated assessment went through a period of introspection (Dowlatabadi, 1995; Grubb, 1993; Henderson-Sellers, 1996; Kolstad, 1998; Morgan and Dowlatabadi, 1996; Parson, 1995, 1996; Risbey *et al.*, 1996; Rotmans and van Asselt, 1996; Rotmans, 1998; Rotmans and Dowlatabadi, 1998; Schneider, 1997; Shackley *et al.*, 1998a,b; Thompson, 1997; Tol and Vellinga, 1998; Toth and Hizsnyik, 1998; Weyant *et al.*, 1996). Around 1995, very different types of models had emerged – all under the label of integrated assessment modelling – and a new breed of integrated assessment – now known as participatory integrated assessment – challenged the models. The IA community was split into two, perhaps three or four camps: policy simulation modellers (Alcamo and Kreileman, 1996; Morita *et al.*, 1994; Rotmans *et al.*, 1990) were pitted against policy optimisation modellers (Carraro and Galeotti, 1996; Maddison, 1995; Manne *et al.*, 1995; Nordhaus, 1994; Peck and Teisberg, 1992, Richels and Edmonds, 1995; Tol, 1997; Wigley *et al.*, 1996), with a few uncertainty modellers claiming that both had it wrong (Dowlatabadi and Morgan, 1993; Plambeck *et al.*, 1997; van Asselt *et al.*, 1996; Yohe and Wallace, 1996), and those advocating participatory integrated assessment methods arguing for a much reduced role of models in policy advice, and for a drastic overhaul of the models as well (Bailey, 1997; Bailey *et al.*, 1996; Cohen 1997; C. Jaeger, 1998; J. Jaeger, 1998; Munda, 1996; Parson, 1997). Fundamental questions were asked, such as what is integrated assessment, and what is it good for? The European Forum on Integrated Environmental Assessment was one of the results of this process of introspection, as integrated assessors realised that, however great the differences, they have more in common with each other than with disciplinary researchers.

Now, some 10 years later, the situation has changed considerably. Integrated assessment has become widely accepted, although practice lags behind. Integrated assessment modelling has become an accepted tool in many circles (Ayres, 1997; Chan *et al.*, 1999; Dey, 2002; Falconi-Benitez, 2001; Sands and Leimbach, 2003; Watanabe *et al.*, 2005), and IA modellers seem more concerned about the day to day business of applying and developing their models and databases than about the grand questions of the philosophy of science. Yet, a quiet revolution is taking place, as integrated assessment models are increasingly challenged by earth system models of intermediate complexity and, in the not too distant future, full complexity models. (We delineate the difference between these types of models below.)

This chapter discusses integrated assessment models, what they are, what they are for, how integrated assessment models have changed over the last decade, and what direction they may need to take in the next decade to meet new challenges. We particularly focus on (1) the developments in the field over the last five years or so; and (2) the further development needed to enhance multidisciplinarity and policy-relevance.

Integrated assessment models support integrated assessment. There are many definitions of integrated assessment. Tol and Vellinga (1997) review these definitions, and find that they all characterise integrated (environmental) assessment as multidisciplinary, policy-relevant research. Integrated assessment models are therefore models that combine knowledge from multiple disciplines, with the aim of shedding light on policy questions.

Integrated assessment is more than integrated assessment modelling (Hisschemöller *et al.*, 2001). Other important components of integrated assessment, indeed any field, are defining the issues, formulating the policy questions, and interpreting and communicating the results. These things are best done in larger groups of researchers and policy makers. Sometimes, it is too hard to combine disciplinary knowledge into a coupled model; in those cases, expert panels may provide the multidisciplinary integration.

Some have argued that such panels should include laypeople, and even that laypeople should be involved in the modelling (Funtowicz and Ravetz, 1994; Gough *et al.*, 1998; O'Connor *et al.*, 1996; Kasemir *et al.*, 2000; Schlumpf *et al.*, 2001; Siebenhüner and Barth, 2005). We reject such notions. Expert panels should include experts only, noting that one does not need an academic position or title to qualify as an expert.[1] Including non-experts in modelling is even worse. If my car is broken, I select a garage: Tlokweng Road Speedy Motors; I explain the problem to the mechanic; and I assess the result after he is done. I do not interfere with Mr J.L.B. Matekoni while he is fixing my car, as that would waste his time and mine, and would violate the trust I placed in him by selecting him as my mechanic. Like car repair is best left to mechanics, modelling is best left to modellers.[2]

Section 2 discusses types of integrated assessment models, their structures, purposes, strengths and weaknesses. Section 3 reviews policy-optimisation models. Section 4 treats policy-evaluation models. Section 5 turns to issues of uncertainty. These three sections each discuss the purpose of the models, recent developments, and current trends. Section 6 combines these into an overall assessment of the field.

2. Types of integrated assessment models

Weyant *et al.* (1996) survey the field of integrated assessment models for climate change.[3] With a few exceptions – notably, acidification (ApSimon and Warren, 1996; Foell, 1995; Hordijk, 1995; Hordijk and Kroeze, 1997; Posch *et al.*, 1996; Warren and ApSimon, 2000) – the field of integrated assessment modelling is still dominated by analyses of climate change. We briefly summarise the main findings from Weyant *et al.* (1996) before turning to the developments since 1996.

Weyant *et al.* (1996) offer a two-dimensional classification of integrated assessment models. Firstly, there is a distinction between policy-optimisation and policy-evaluation models. The latter take a small set of policies and policy proposal and consequences of these policies in a "what-if" exercise. Consequences are assessed with a more or less formalised set of indicators of environmental quality and economic welfare. Policy-optimisation models, on the other

[1] At the same time, an academic position does not guarantee expertise.
[2] Note that many excellent experts and academics are also rather hopeless at modelling.
[3] See also the references in the first paragraph of the introduction.

hand, include a strictly formal, uni-dimensional assessment of "better" and "worse" outcomes, and use this to select, from a large number of what-if exercises, the "optimal" policy.

The distinction between policy-optimisation and policy-evaluation models coincides with many other distinctions. Policy-optimisation models tend to be developed by economists, who often tend to normative solutions to policy problems; the models tend to be small, with little spatial or temporal resolution; and the models tend to depict the world as smooth and robust. Policy-evaluation models tend to be developed by natural scientists; the models tend to be large, with considerable spatial and temporal details; the models tend to picture the world as strongly non-linear with potential catastrophes.

The second distinction between integrated assessment models is the treatment of uncertainty. Some modellers try to represent the system as well as possible, the so-called kitchen-sink approach. Uncertainties are countered by adding ever greater detail to the model.[4] Other modellers argue that as good as can is not good enough, and try to represent the uncertainties as well as possible. Because uncertainty analyses are computationally demanding, "uncertainty models" tend to be smaller and less complex than their "certainty equivalents". There are policy-optimisation models under certainty as well as uncertainty, and there are policy-evaluation models with and without uncertainty.

In the review of Weyant *et al.* (1996), the discussion of policy-optimisation models is focused on the determinants of welfare-maximising and cost-minimising emission reduction trajectories, particularly with regard to near-term emission abatement. Little attention is paid to issues of intra- and intergenerational equity; of international cooperation; of land use change and other gases; and of technological development. In the discussion of policy-evaluation models, the review emphasizes the carbon cycle, land use change, and sulphur aerosols. Little attention is paid to tolerable windows and incorporating lay knowledge. For both types of models, the review pays attention to parametric uncertainty only, and mentions the embedding of climate change in global change only in passing.[5] On these points, substantial progress has been made in the last decade.

Recently, earth system models have been added to the stable of integrated assessment models. Earth system models, like integrated assessment models, aim to describe the entire earth system, coupling models that describe the various components. A crucial distinction between earth system models and integrated assessment models is that the latter are designed for giving policy advice, whereas the former are more curiosity driven. Earth system models come in two flavours: intermediate complexity and state-of-the-art.[6]

Earth system models of intermediate complexity (EMICs; see Claussen *et al.*, 2002, for an overview) are akin to policy-evaluation integrated assessment models, and the distinctions and communities are fluid. EMICs are multidisciplinary, but they were developed for improved understanding of the evolution of the earth system at geological time scales. As humans had little influence in the remote past, their activities tend to be underrepresented in these models. However, EMICs are increasingly used for future scenarios and consequently modellers are trying to include human activities.

Models of intermediate complexity compute much faster than full complexity earth system models. Nonetheless, state-of-the-art coupled atmosphere-ocean general circulation models gradually morph into earth system models, including more and more detailed representations not just of the physics (e.g., ice sheets) but also of the biology and chemistry of the earth

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[4] Including what goes on in the kitchen sink; this term probably originated in hydrology.

[5] The Third Assessment Report of the IPCC does not contain a separate discussion of integrated assessment or integrated assessment modelling.

[6] As such, integrated assessment models may be called simple earth system models.

system (e.g., Berthelot *et al.*, 2002; Betts *et al.*, 2004; Cox *et al.*, 2004) In time, human activities will have to be included as well.

Like the classification of integrated assessment models of Weyant *et al.* (1996), earth system models are best ranked on a dual scale of comprehensiveness and complexity. The more comprehensively integrated models tend to have less detail and less complexity (per component), while the more complex and detailed models tend to include a smaller range of components. The simpler models are more amenable to uncertainty analysis.

However, with integrated assessment models we found that the simpler/more comprehensive models are better suited for strategic policy advice for the long run, as they focus on the big picture. The more complex/less comprehensive integrated assessment models are better at assessing the details of tactical policy questions, as the details become exceedingly uncertain in the long run and blur the main findings. However, full complexity earth system models rely less on parameterisation and more on processes, and so are valid in the long run as well as in the short run. It is computing power more than anything else that restricts the range of applications of full complexity earth system models.

3. Policy optimisation models

3.1. Cost-benefit analysis

In a cost-benefit analysis, the costs of a policy intervention are weighed against its benefits so as to determine the optimal intensity of the intervention. In the case of climate change, the costs are the costs of greenhouse gas emission abatement (Hourcade *et al.*, 1996, 2001); the benefits are the avoided impacts of global warming (Pearce *et al.*, 1996; Smith *et al.*, 2001). Ideally, a cost-benefit analysis is comprehensive in that it includes all costs and benefits. In practice, only the measurable costs and benefits are included, which leads to distortions and biases (of unknown sign; Smith *et al.*, 2001). A cost-benefit analysis should reflect impacts on people's well-being. In practice, costs and benefits are often expressed in terms of the equivalent effect on people's income, a necessary but potentially misleading simplification (Braden and Kolstad, 1991; Champ *et al.*, 2003). In theory, cost-benefit analysis is based on observed preferences. In practice, observations are combined with conjectures, particularly in the form of benefit transfer (Brouwer *et al.*, 1999; van den Bergh *et al.*, 1997; Woodward and Wui, 2000). Cost-benefit analyses take a rather technocratic perspective (Adams, 1996; Munda, 1996; Pearce, 1976; Portney, 1998). A benevolent dictator decides on the optimal course of action. This can be justified as follows. The result of a cost-benefit analysis is the best possible outcome;[7] other, more realistic policies have to be compared against this. The aim of cost-benefit analysis is economic efficiency, which implies that, in principle, no one is worse while some are better off.

The prototype of all cost-benefit analyses of climate change is Nordhaus' DICE model (Nordhaus, 1992, 1993, 1994). DICE combines a simple model of economic growth – a Ramsey-Cass-Koopmans model (Cass, 1965; Koopmans, 1967; Ramsey, 1928) – with a simple model of carbon cycle and climate – the Schneider-Thompson (1981) model. The two models are basic. The only interesting thing about the DICE model is that it considers the interactions between the economic and the climate system. The DICE model sparked a lively line of research (Kolstad, 1996; Manne *et al.*, 1995; Nordhaus and Boyer, 2000; Nordhaus and Popp, 1997; Peck and Teisberg, 1992; Pizer, 1999; Popp, 2004), although the model has

[7] Although one may debate the notions of "better" and "best".

many obvious shortcomings (Joos *et al.*, 1997; Kaufmann, 1997; Moss *et al.*, 2001; Tol, 1994). Although the current models have progressed considerably in the representation of economy and technology, they are still basically the same as their prototype with regard to the link to the natural science components. The reasons for DICE's success and the reasons for this remarkable lack of progress are the same, as outlined below.

In a cost-benefit analysis, the costs of greenhouse gas emission reduction are compared to its benefits, i.e., the avoided costs of climate change. In order to do so, the carbon cycle and climate models have to be an integral part of the economic model. One cannot get away with adjusting boundary conditions or the like; the dynamics of climate and economy are co-determined in a cost-benefit analysis.[8]

Fully integrating climate and economic models is hard, because the models are so different. Climate models work in a simple geography, where close is close and far is far. Economic geography is more complicated, as events far away (Chicago, Redmond, Tokyo) can be much more important than events close by. Time is different as well, as economic agents have memories and try to plan the future whereas natural agents merely react to the immediate past. Thirdly, climate models are simulation models; they model the climate where, when and as it is. Economic models are equilibrium models; they model where the economy is moving to; growth models track the "economic attractor" over time, but not the actual state of the economy. See Romer (1996) for a more detailed discussion.

If one looks at a large enough spatial and temporal scale, these differences disappear together with any kind of detail. Therein lies the genius of the DICE model. By taking time steps of ten year, the pseudo-time of the economic model and the real-time of the climate model converge. By nesting the climate model into the economic model, the economic agents can retain their forward-looking behaviour while the natural agents are myopic. By looking at the world as a whole, geography disappears.

At the same time, models like DICE can only answer very simple questions. More elaborate questions require more detail in both space and time. That, unfortunately, cannot be realised in a DICE-like model.

People have tried, though. Notably, the economy has been regionalised without, however, also regionalising the climate (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000). Did the global decision maker of the DICE model reduce emissions only moderately, non-cooperative games suggest that rational emission abatement would be even less (Escapa and Gutierrez, 1997; Eyckmans, 1997; Fankhauser and Kverndokk, 1996; Hamaide and Boland, 2000; Yang, 2003) – and that the global cooperation between countries, implicitly assumed by Nordhaus, is unstable (Barrett, 1994; Carraro and Siniscalco, 1992, 1993; Hoel, 1994; Kemfert *et al.*, 2004; Tol, 2001a); see Eykmans and Tulkens (2003) for a dissenting position.

These conclusions are based on so-called Nash behaviour, be it in a Nash equilibrium or in a cartel game; with Nash behaviour, agents do not anticipate changes in the behaviour of other agents. Games with alternative formulations of behaviour are less pessimistic on the prospects of cooperation, but the mathematics are so complex that these techniques are only beginning to be applied to even simple coupled climate-economy models (Eyckmans, 2001).

Issue linkage is another possibility for increasing stability. With issue linkage, previously separate negotiations on different issues are combined. However, issue linkage is no panacea. Ideally, one would link climate policy to a global commons good with asymmetries that are opposite to the asymmetries of greenhouse gas emission reduction. However, that global good

[8] As cost-benefit analysis typically requires running many scenarios, the model components need to be tightly coupled.

is unidentified. Alternatively, one could link to a club good,[9] but that may be problematic from the perspective of the club good (Carraro and Marchiori, 2004).

In an interesting new development, Currarini and Tulkens (2004) abandon the assumption of a singular nation; and replace it with governments simultaneously negotiating with one another and with their electorate. This reduces the number of stable agreements. Unfortunately, they solve this for flow pollution only.

One conclusion that stands out in the game-theoretic literature is that, if the poorer countries are more vulnerable to climate change, they should be most active in reducing emissions (e.g., Tol, 1997). Reality is different. The intuitive explanation is that developing countries have more urgent things on their mind than climatic change. Current integrated assessment models narrowly focus on climate change so that, unfortunately, this conjecture still has to be tested with a serious modelling.

Economic growth is supposed to be driven by the accumulation of capital and the accumulation of knowledge (e.g., Romer, 1996). The growth models used in earlier integrated assessment models of climate change only included the first process; technological progress was like "manna from heaven". Perhaps the most significant innovation in the cost-benefit analysis of climate change is that the description of economic growth is now more complete; endogenous technological change is now part of many models (Buananno et al., 2001; Fischer *et al.*, 2003; Gerlagh and van der Zwaan, 2002, 2003; Goulder and Mathai, 2000; Goulder and Schneider, 1999; Manne and Richels, 2004; Messner, 1996; Miketa and Schrattenholzer, 2004; Riahi *et al.*, 2004). However, the empirical applications still leave much to be desired. Firstly, the data, on which these new models are based, are of insufficient quality for the simple but fundamental reason that technology is hard to define and measure (McDonald and Schrattenholzer, 2001; Newell *et al.*, 1999; Popp, 2002). Secondly, although the speed and direction of technological progress is crucial for greenhouse gas emissions in the long run, it is far from clear how policy could and should steer and accelerate technological change (Newell *et al.*, 1999; Jaffe *et al.*, 2002; Jaffe and Trajtenberg, 2002).

In a perhaps a more academic development, research now also begins to pay systematic attention to issues of equity, and the important trade-offs that underlie allocating resources to greenhouse gas emission reduction rather than to other worthy causes (Bosello *et al.*, 2004; Bosello and Roson, 2002; Bürgenmeier, 2003; Byrne *et al.*, 1998; Farrow, 1998; Ikeme, 2003; LeCocq *et al.*, 2000; Mitra, 2000; Müller, 2001; Rose *et al.*, 1998; Rose and Stevens, 1993; Shiell, 2003; Tonn, 2003; Toth, 1999; Yohe *et al.*, 2000). A few papers underline the importance of equity issues in climate change, and demonstrate that superficial claims of "justice" or "goodness" can actually bring about consequences that are the opposite of the intended results (Kemfert and Tol, 2002; Tol, 2001b, 2002). Other studies focus on issues of equity and responsibility for greenhouse gas emissions (Rigdley, 1993; Sagar, 2000; Sugiyama and Deshun, 2004; Tol and Verheyen, 2004). Most importantly, however, these papers demonstrate that equity is important and complex, that it can be subject to rigorous study, and that this should be done.

Closer to policy, the research on climate change impacts has embraced the notion of adaptive capacity (Burton, 1994, 1997; Fankhauser *et al.*, 1999; Hanemann, 2000; Kelly and Adger, 2000; Klein, 1998; Mendelsohn, 2000; Parson et al., 2003; Smit *et al.*, 2000; Smith *et al.*, 1996; Yohe, 2000; Yohe and Tol, 2002). Adaptive capacity allows one to model the ability of a system to adapt, rather than adaptation itself. This distinction is crucial, as adaptation takes places at a finer scale than the model resolves, and adaptation decisions are made by different

[9] With a global commons good, it is in every country's individual interest to free-ride on the international agreement, even though free-riding is at odds with the international interest. With a club good, it is in every country's self-interest to join the treaty. Examples include free trade agreements and technology sharing.

policy makers than an integrated assessment model seeks to advice (Tol, forthcoming, d). Including adaptive capacity allows for a better assessment of the trade-off between mitigation and adaptation. In models with static vulnerability, the trade-off is between the costs of emission abatement and the benefits of avoided climate change. In models with dynamic vulnerability, the trade-off is between the costs of emission abatement including the changed adaptive capacity, and the benefits of avoided climate change (Tol and Dowlatabadi, 2001; Tol, forthcoming a,b,c).

3.2. Cost-effectiveness analysis

The crucial difference between cost-benefit and cost-effectiveness analysis is that, in the former, the analysis compares the costs and the benefits of a policy intervention whereas the latter is restricted to the costs. A cost-effectiveness analysis seeks the cheapest way of reaching a goal. The goal itself is determined outside of the analysis. For the rest, cost-effectiveness analysis provides a technocratic yardstick aiming for the greatest good for the greatest number, just like cost-benefit analysis.

Cost-effectiveness analysis thus avoids the tricky business of comparing costs and benefits in a common metric. This also implies that the integration does not need to be as comprehensive, which allows for more detail and complexity in the components that are included.[10] If, for instance, the atmospheric concentration of carbon dioxide is the policy target, then one does not need to model climate change or its impacts;[11] CO_2 concentrations suffice. This implies that cost-effectiveness models do not suffer from the same methodological difficulties as do cost-benefit models; and, consequently, that progress has been more rapid.

Nonetheless, cost-effectiveness IAMs of climate change have difficulty keeping up with the policy agenda. This is a clear illustration of the tension between the demands of policy advice and the supply of high-quality research. 75% of the climate problem is due to carbon dioxide; 75% of carbon dioxide emissions come from fossil fuel combustion; 75% of fossil fuels are use in industry and household. It is therefore no surprise that energy economists dominate climate economics. However, $0.75^3=0.42$. This justifies a call for wider climate policy analysis.

Transport is responsible for some 25% of carbon dioxide emissions from fossil fuel combustion. Transport is therefore an important sector for reducing emissions (Michaelis *et al.*, 1996). However, the analysis of transport combines awkwardly with the analysis of the other uses of fossil energy. Energy is a necessary input for a large variety of activities; energy is internationally traded, and so are many energy-intensive products. Therefore, one needs a multi-region, multi-sector trade model to appropriately reproduce the market of energy and energy-intensive goods. The problem with most computable general equilibrium models is that they assume instantaneous and costless transport (Ginsburgh and Keyzer, 1997). For most practical purposes, the implications of this assumption can be counteracted through calibration. A realistic transport sector, however, would require a different model set-up, one in which transport is not reduced to Armington elasticities, constant costs, or, in the most advanced CGEs, icebergs.

[10] This implies that all problems with computing the costs of greenhouse gas emission reduction in cost-effectiveness analyses, also hold for cost-benefit analysis.

[11] That is, if climate change impacts do not affect abatement efforts or costs, or the no control scenario (cf. Fankhauser and Tol, 2005).

Similarly, multi-region computable general equilibrium models assume that the constituent regions are homogenous areas, with economic activity spread evenly over the land area.[12] Again, this assumption is innocent for most applications, but land use is an exception to that. Land use change is responsible for some 25% of carbon dioxide emissions; while biofuels and afforestation are prime options to reduce (net) emissions (Leemans and Zuidema, 1995; Sands and Leimbach, 2003; Edmonds *et al.*, 2004; Fischer and Schrattenholzer, 2001; Schneider and McCarl, 2003).

Other greenhouse gases account for some 25% of the climate problem. Some of these gases (methane, nitrous oxide) originate to a large extent from agriculture and other forms of land use (change). Methane has the additional problem that its behaviour in the atmosphere is considerably more complex than that of the other greenhouse gases, so that a comprehensive analysis would need to include the emissions of a whole suite of emissions more commonly associated with conventional air pollution. Other greenhouse gases (HCFs, PFCs, SF_6) come from highly specialised industrial applications, occurring at a scale that is hard to represent in an economy-wide model. In this particular area, rapid progress has been made, particularly in the context of the Energy Modeling Forum, round 21, results of which will be published soon. The most important integrated assessment models of climate change are now capable of handling the various trade-offs between the various greenhouse gases, and through intercomparison of model results, the understanding of this issue has leaped forward.

Another area with substantial progress is technological change. However, as with cost-benefit models, although endogenous technological change is now reasonably well-understood at a conceptual level, the numerical results are limited by the lack of quality of the data (cf. references above).

4. Policy evaluation models

4.1. Classical policy evaluation models

The originally prominent policy-evaluation models (IMAGE, IIASA, MIT, SGM, AIM) have maintained their position, and a few models have been added to the stable (DART, GTEM, PACE). They have offered quantitative insights into a range of policy proposals. The models themselves have been updated with the latest insights and data, and have been extended to include more feedbacks and processes, with a particular emphasis on land use, nature and other environmental problems (Bouwman *et al.*, 2002; Leemans and Eickhout; Felzer *et al.*, 2004; Rensen and Knoop, 2000; Sands and Leimbach, 2003; van Minnen *et al.*, 2000) and on extending the technological array (Edmonds *et al.*, 2004; Fischer and Schrattenholzer, 2001; Kainuma et al., 2004; McFarland *et al.*, 2004; Riahi *et al.*, 2004).

The teams at IIASA, MIT and NIES do not have a single integrated assessment model, but rather a system of standalone models, designed to communicate with one another. On the other hand, the RIVM team runs a single, integrated model: IMAGE (Alcamo *et al.*, 1998). The advantage of standalone models is that fewer concessions need to be made to the overall framework. However, loosely coupled models typically suffer from inconsistencies, and they cannot be used for policy optimisation exercises.

[12] This results from the assumption of non-increasing returns to scale, needed to keep the dynamics in check; see Jaeger and Tol (2002).

DART (Klepper and Springer, 2003), GTEM (Jakeman *et al.*, 2004), PACE (Boehringer and Welsch, 2004) and SGM (Sands, 2004) are multi-region, multi-sector computable general equilibrium models, with environmental models added. In these models, the environmental part is just complex enough to derive the necessary information for the economic and policy analyses. On the other hand, the IMAGE model (Alcamo *et al.*, 1998) is largely an environmental model, with the economic part just complex enough to derive the necessary information for the environmental and policy analyses.

4.2. Policy guidance models

Whereas classical policy evaluation models restrict themselves to computing the environmental and social consequences of a policy proposal or hypothetical policy, a new twist emerged with concepts such as "safe corridors" and "tolerable windows". Proponents of this style of analysis claim that this is an entirely new breed of integrated assessment models altogether, and coined the term "policy guidance" models (Bruckner *et al.*, 2003; Kriegler and Bruckner, 2004; Petschel-Held *et al.*, 1999; Toth *et al.*, 2002; see also Dowlatabadi, 1999; Yohe, 1999). However, as the models are much the same as the classical policy evaluation models,[13] and as these models continue to abstain from a simple definition of what is "good" about a policy, we prefer to treat policy guidance models as policy evaluation models.

The policy guidance flavour of policy evaluation models set constraints on the outcomes of policy strategies. Unlike cost-effectiveness models, these are not constraints as in an optimisation, as the constraints may not be binding. Rather, policies may meet the constraints or they may do better. The set of policies that meet the constraints are deemed "safe" or "tolerable". As with "optimal" in policy optimisation models, "safe" and "tolerable" cannot be unambiguously defined. In applications, "safe" or "tolerable" are defined by a small group of experts and stakeholders.

Constraints may be that the global mean temperature increase should not exceed 0.2°C/decade (Azar and Rodhe, 1997; Swart *et al.*, 1989; Swart and Hootsmans, 1991), that annual emission reduction costs should be below 1% of GDP, or that poor countries should attain a certain level of development.[14] Constraints may be large in number, but in practice it turns out that only a handful really constrain the policy set. If the constraints are lenient, many policies are deemed "safe" but the models do not provide guidance as to which policy to choose from this multitude, even though the environmental and social consequences may be radically different. If the constraints are strict, the "tolerable" policy set gets smaller, and may even be empty (Tol, 1999). In the latter case, there is no policy that satisfies all demands at the same time. The constraints have to be loosened, but again without clear guidance which constraint is more important.

4.3. Agent based models

Agent based or social simulation models (Downing *et al.*, 2001; Pahl-Wostl, 2002; Pahl-Wostl and Hare, 2004) seem to be the preferred answer of the natural science oriented part of the integrated assessment modelling community to the earlier challenge of the omission of the "human dimensions" of global change.[15] Models developed in the social sciences, and

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[13] A number of people in the field of integrated assessment have a tendency to give new labels to old methods, claiming to be innovative.
[14] The last two options have not been analysed.
[15] The term "human dimensions of global change" is interesting. Although not clearly defined, it seems to encompass both processes within individual human beings and interactions, both material and immaterial, between human beings. It is clear that this includes all behavioural and social sciences, and perhaps some of the

particularly in economics, are of course also based on agents. However, there is a crucial distinction between economic and agent-based models. The agents in economic models have postulated motives, from which behaviour and interactions are derived. The agents in agent-based model have postulated behaviour, from which interactions are derived. Adding additional process knowledge often reduces the number of degrees of freedom in calibrating the model. Therefore, agent-based models can more easily "reproduce" observations, as more parameters can be tuned. In return, adding process knowledge typically increases the robustness of extrapolation, as tuned models may only be valid within the range of calibration. Compared to economic models, social simulation models have a better fit with the past, but reduced forecasting ability. Economists have therefore largely abandoned this line of inquiry since Samuelson (1944).

5. Uncertainty in models

Around 1995, there were two major foci in integrated assessment modelling under uncertainty. On the one hand, there were models that sought to portray the uncertainties by estimating the probability density functions of key parameters (e.g., Plambeck and Hope, 1996, 1997). On the other hand, there were models that had a much simpler representation of the uncertainties, but removed them over time to see what effect such "learning" would have on policy choice (e.g., Kolstad, 1996; Manne and Richels, 1995).

Both activities continue, but with methods and detail that refine earlier work. Webster *et al.* (2003) is a recent example of estimating probability density functions. Instead of using simple models (as done in around 1995), Webster *et al.* (2003) use more complex models – although in some cases, a model component was replaced with a reduced form. Where possible, the models were constrained by observations (Forest *et al.*, 2002). However, the resulting estimate of the uncertainty is not unlike previous estimates. In climate modelling, ensembles simulations are gaining ground. Complex models are run either with different starting conditions, or with different parameterisations. The result is an assessment of the uncertainty of the results (Palmer, 2000). These techniques are now implemented for earth system models as well (Hewitt and Griggs, 2004).

Recent papers on uncertainty and learning include Nordhaus and Popp (1997) and Webster (2002). A major step forward is the work of Kelly and Kolstad (2001), in which learning is no longer exogenous, but depends on the observations made by the agents in the model. The papers by Ulph and Ulph (1997) and Ulph and Maddison (1997) show that the insights from a single-decision-maker framework do not carry over to a situation with multiple decision makers. Baker (2005) shows that the results of perfect learning (assumed in most other papers) do not carry over to partial learning.

Methodological progress is also seen in the application of the work on irreversibility, stochasticity and learning by Dixit and Pindyck (1994). Applications to climate change include Pindyck (2000, 2002), Fisher and Narain (2003) and Zhu and Weyant (2003). Although the methodology allows only for very simple models, "option value theory" leads to qualitatively different results than does "cost-benefit analysis under uncertainty". Particularly, irreversibilities are considerably more important. In climate change, it is still an open question

arts as well. It is not clear that the term "human dimensions" is particularly appealing to any of these disciplines, and it is definitely not an established term within the behavioural and social sciences. Equivalent descriptions of the natural sciences would be the "abiotic dimensions" and "biotic dimensions".

whether the irreversibilities in the climate system are more important than the irreversibilities in the energy system (Kolstad, 1994).

An understanding of the uncertainties is needed for policy advice, but the implications are unclear. Reichert and Borsuk (2005) emphasize that it is not the uncertainty about the state that matters, but rather the uncertainty about the change in the state, brought about by the policy intervention. Uncertainty and learning is usually applied to cost-effectiveness analysis. Most studies agree that uncertainty increases the stringency of near-term emissions targets. Estimation of the probability density function is typically done in scenario analysis, but it is also applied to cost-benefit analysis. Tol (2003) argues that the uncertainty about climate change may be too large for the assumptions of cost-benefit analysis to hold. This would call for policy analysis based on safe minimum standards rather than cost-benefit analysis. However, Tol (1999) argues that, under uncertainty, the tolerable window – the climate change incarnation of safe minimum standards – may be empty. Lempert et al. (1996, 2000) argue in favour of robust rather than optimal policy analysis as a way of dealing with deep uncertainty.

6. The challenge of model coupling

6.1. The issues

The components of current earth systems models originate in the natural sciences. This holds for both state-of-the-art models and models of intermediate complexity. Integrated assessment models, which may be classified as simple earth system models, typically combine models from the natural and the social sciences, but these models are small enough to allow integration of the model code by a single team, even a single person. That option is not open for larger and more complex earth system models. Yet, if earth system models want to truly describe and predict the earth system, they would need to include the major agent of global change, namely *homo sapiens sapiens*. An earth system model with a proper description of the anthroposphere will not be there for the foreseeable future, but the task is so formidable that research must commence now. The experience of integrated assessment modelling may prove useful.

Models of human behaviour, of interactions between humans, and of interactions between humans and their environment – here termed economic models, as the other social sciences have contributed very little to formal models – are different from models in the natural sciences. This is partly because many economic models were developed for other purposes than studying global change. Another reason is that the intellectual tradition in economic modelling has been separate from that in the natural sciences. This implies that either economic or natural scientific models will have to be reformulated, but in such a way that research questions and model structures are still recognisable to the larger professions.

A third reason is that the anthroposphere is truly different. Whereas natural systems primarily interact with their intermediate environment, social systems operate in a different geometry, where physical distance is of secondary concern. Instead, administrative boundaries, political allies, trade partners, access to information, social classes, and economic sectors play a defining role in "economic space". The implication is that we need to develop a mapping from natural to economic space and back.

Another true difference is that people plan, whereas "natural agents" react.[16] In the economy, the future may influence the present – or rather, expectations about the future influence the present. This implies that the mental models of the economic agents need to be added to the model of the earth system, including the ability of agents to learn about their environment.

Because of the above reasons,[17] economic models are typically formulated as equilibrium models, where the equilibrium may well be a dynamic one. Natural science models usually include richer dynamics. Therefore, if the two types of models are to be coupled at a matching level of complexity, economic models need to be extended to variability and disequilibrium dynamics, both in time and in space, or natural science models need to be reduced to their dynamic equilibrium. Of course, if the fine-scale dynamics of one system are irrelevant to the other system, then matching complexity is not needed.

6.2. Dynamic simulation models of the economy

Most of the more complex economic models used for integrated assessment models are so-called recursive-dynamic computable general equilibrium models (Ginsburgh and Keyzer, 1997). In every period, the model is in a market equilibrium. Over time, this type of model is a simulation model. It can therefore readily to be coupled to simulation models of the environment.

However, the time step used in a recursive-dynamic CGE cannot be much shorter than 5 years, because this would violate the equilibrium assumptions within the period. If the short term variability of the economy is important to the questions at hand, the pragmatic alternative would be to use a business cycle model. These models, however, have the disadvantage that they are applicable in the short run only (Romer, 1996).

The general equilibrium is equivalent to the Nash equilibrium of a non-cooperative game (e.g., Russell and Wilkinson, 1979). Evolutionary game theory is a relatively new field. In these models, behaviour at the long term is similar if not identical to that in a Nash equilibrium. In the short term, however, behaviour is much richer (Samuelson, 1997; Weibull, 1995). Evolutionary game theory may provide the methods to consistently model both variability and trends in the economy. However, evolutionary game models are highly stylised, with applications only at the small scale (e.g., Sethi and Somanathan, 1996).

6.3. General equilibrium models of the natural system

There is a long tradition of bioeconomic modelling in fisheries economics. The prime interest of these models is in policies that would help to preserve fish stocks, to which end models of the behaviour of fishing fleets are coupled to models of the behaviour of fish stocks. Typically, the fish stock dynamics are stripped to their barest essentials, much like carbon cycle and climate are in the current integrated assessment models (Anderson, 2002a,b; Hodgson, 1995).

John Tschirhart (2000, 2002, 2003, 2004; Finoff and Tschirhart, 2003a,b; Pethig and Tschirhart, 2001) has set out to change this. In general equilibrium models of economies, agents maximise their well-being given their initial endowments, their production technologies, and their abilities to exchange with other agents. In his general equilibrium models of ecologies, agents maximise their net energy given their initial endowments, their

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[16] There is dispute over the planning abilities of higher animals; these animals do not play a major role in global change, however.

[17] And because economies are assumed to converge to their equilibrium (Jaeger and Tol, 2002) and rapidly so (Romer, 1996).

transformation technologies, and their abilities to prey on other agents.[18] Economic agents save and invest in capital. Ecological agents invest their excess energy in reproduction. The first applications of general equilibrium models of ecosystems are promising. Coupled economy-ecology general equilibrium models are conceptually straightforward.

Extending these models to chemistry and physics is less straightforward. Although many physical processes can be described as optimisation problems, this is typical for the very fine scale, and less useful for the larger scales necessary for global change analysis. However, there should be no conceptual problems as long as the physical and chemical system can be modelled as changes in endowments or productivities (Berrittella *et al.*, 2004; Bosello *et al.*, 2004a,b).

Various groups have used endowment and productivity changes to put the impacts of climate change in computable general equilibrium models. This was done first for agriculture (Darwin, 1997; Kane *et al.*, 1992; Reilly *et al.*, 1994; Rosenzweig et al., 1993). Other studies include Darwin and Tol (2001) and Bosello *et al.* (2004a) for sea level rise, Berritella *et al.* (2004) for tourism, Bosello *et al.* (2004b) for health, Darwin *et al.* (1996) for nature protection, and Jorgenson *et al.* (2004) for all market impacts of climate change.

7. The road ahead

Over the last ten years, integrated assessment modelling has matured and transformed itself. It has matured in the sense that the "identity debate" that raged around 1995 is over. Integrated assessment modelling is now an accepted way of doing research and advising policy, in climate change, in acidification, and increasingly in other areas of global environmental change as well. Integrated assessment models have developed from crude and clumsy tools to sophisticated frameworks that can answer many of the questions that stakeholders may have.

While Weyant *et al.* (1996) where able to review the whole field of integrated assessment modelling for climate change in a single chapter, the current chapter shows that – for a detailed review – more space is needed. This is another sign of maturity.

At the same time, although integrated assessment models have improved their policy-relevance – the assessment part – the coupling of natural and social science models – the integration part – has largely stalled. This uneven development is understandable, as integrated assessment modelling is financed for its policy advice. It may be worrying, as integrated assessment models derive their superiority in policy advice from their integration. The scientific excitement is also in the integration, rather than in the assessment.

However, even though further integration has been slow in the main workhorses of integrated assessment modelling, considerable progress has been made elsewhere. This suggests that either new, better integrated models will appear or that old models will be overhauled. This is needed to answer the policy questions of the next decade, which centre around the long term targets of climate policy and the strategies needed to achieve these goals.

[18] The notion of optimising biological agents is not new. For example, the trees in the LPJ model optimise their net primary production (akin to Tschirrhart' net energy); the height distribution of photosynthetic activity is also based on optimisation (Haxeltine, personal communication, 2004).

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