Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions?

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One of the principal tools used in the integrated assessment (IA) of environmental science, technology and policy problems is integrated assessment models (IAMs). These models are often comprised of many sub-models adopted from a wide range of disciplines. A multi-disciplinary tool kit is presented, from which three decades of IA of global climatic change issues have tapped. A distinction between multi- and inter-disciplinarity is suggested, hinging on the synergistic value added for the latter. Then, a hierarchy of five generations of IAMs are proposed, roughly paralleling the development of IAMs as they incorporated more components of the coupled physical, biological and social scientific disciplines needed to address a "real world" problem like climatic change impacts and policy responses. The need for validation protocols and exploration of predictability limits is also emphasized. The critical importance of making value-laden assumptions highly transparent in both natural and social scientific components of IAMs is stressed, and it is suggested that incorporating decision-makers and other citizens into the early design of IAMs can help with this process. The latter could also help IA modelers to offer a large range of value-containing options via menu driven designs. Examples of specific topics which are often not well understood by potential users of IAMs are briefly surveyed, and it is argued that if the assumptions and values embedded in such topics are not made explicit to users, then IAMs, rather than helping to provide us with refined insights, could well hide value-laden assumptions or conditions. In particular, issues of induced technological change, timing of carbon abatement, transients, surprises, adaptation, subjective probability assessment and the use of contemporary spatial variations as a substitute for time evolving changes (what I label "ergodic economics") are given as examples of problematic issues that IA modelers need to explicitly address and make transparent if IAMs are to enlighten more than they conceal. A checklist of six practices which might help to increase transparency of IAMs is offered in the conclusions. Incorporation of decision-makers into all stages of development and use of IAMs is re-emphasized as one safeguard against misunderstanding or misrepresentation of IAM results by lay audiences.

1. Introduction

It is often asserted that human societies are "better off" as we enter the 21st century than were all previous generations. There are many more of us enjoying increasing material standards of living and increasing life expectancy as a result of the explosion in technological developments and social organization in the wake of the industrial revolution. To be sure, progress has had its prices in terms of baffling complexity which disenfranchises average citizens from the decision-making process, loss of traditional values (e.g., the waning of large nuclear families), overcrowding, growing wealth gaps between rich and poor, and, most relevant to global change issues, serious questions about the environmental sustainability of "business-as-usual" development trajectories. Indeed, while most medical studies point toward increasing (though not necessarily sustainable) human health status now compared to centuries ago, few conservation biologists would accept a comparable claim that natural ecosystems are "better off" today given the many disturbances to nature that have been compounded over the centuries: (1) habitat destruction, (2) channeled runoff, (3) invasions of "exotic" species transported by people across natural biogeographic obstacles that otherwise limit their ranges in nature, (4) release of millions of tons of thousands of synthesized chemicals that biological species have no evolutionary experience in dealing with (e.g., DDT or PCBs – see, e.g., Colborn et al. [8]) and, now at a global scale, (5) alterations to the composition of the atmosphere which have caused stratospheric ozone depletion, toxic air pollution and a "discernible" and growing human impact on climate (e.g., IPCC [36]).

Debate is ongoing as to whether these disturbances – individually or synergistically as a combination (e.g., Myers [58], Vitousek [102], Schneider and Root [93]) – will reduce our future quality of life more or less than the material improvements in quality of life brought about by increasing numbers of people demanding higher standards of living and using technology and organizational developments to achieve these growth-oriented goals. But I will not attempt to answer this exceedingly complex, mixed technical/value conundrum in this paper (see Schneider [89] for more on my personal views). Rather, my purpose here is to examine the analytic tools that analysts often turn to in search for rational enlightenment in the bewilderingly complex global climate change policy debate: integrated assessment models (IAMs).

Climate change issues are but a subset of the larger environmental science, technology and policy context often labeled "global change". Global change refers to (1) human disturbances at a global scale (e.g., ozone reduction), and (2) the myriad set of disturbances at regional and local scales often repeated around the globe (e.g., habitat alteration, chemical releases, exotic species invasions or socioeconomic transformations in the areas of technology, demographic patterns, or political organization). Although my principal focus will be on global climate change, its potential synergism with the other global change disturbances should always be borne in mind. In particular, I will briefly and selectively (1) produce tables on the hierarchical development of IAMs in the global climate assessment and policy context, (2) point out directions for future work, (3) suggest ways IAMs can help with the policy-making process, and (4) comment on and present many examples of the dangers that analytic methods with limited capabilities bring to the public debate given that not all potential users of IAM results will be aware of hidden values or assumptions that are inherent in all such tools – now and for the foreseeable future.

Integrated assessment does have the explicit purpose of helping in the decision-making process. Traditional disciplines often evolve to search for explanations of natural or social phenomena. IAs, however, are purposely constructed primarily to address "real world" problems that lie across or at the intersection of many disciplines. Of course, explanation of the behavior of complex and interconnected physical, biological and social systems can itself be enlightened by use of IAMs, regardless of their potential social utility, so we should not overemphasize the "curiosity" versus "policy" driven dichotomy between disciplines and integrated assessment models. But because of the social purposes built into IA by design, and since IAMs are a principal tool that might provide insights into value-laden decision-making processes, IA modelers face the special obligation to make these tools as transparent as possible so that a spectrum of users of greatly varying analytical skills (e.g., see the discussion of "good practice" in IAM by Ravetz [70]) can benefit from any insights that IAM simulations might provide without misinterpreting IAM results given their limited capabilities. And, at the same time, by including many publics into the process of designing and using IAMs, the modelers will likely enrich their own professional activities (e.g., Ravetz [70]).

In the end, policy making is an intuitive judgment about how to manage risks or make investments to deal with a wide array of possible consequences (with a diverse set of computed and postulated probabilities and culturally-dependent judgments on what constitutes "well being"). The role of any analytic method, IAMs included, is to help elucidate how various policy choices could alter the likelihood or costs of various options and/or consequences. For this reason, the discipline of economics, since it has the best developed formalism and empiricism for cost/benefit analyses, is in a particularly advantaged position to contribute to IAMs. However, some have challenged the cost/benefit technique in particular, and the utilitarian principle upon which it rests in general, as incommensurate with the full spectrum of social values (e.g., for undervaluing nature – Ehrlich [16] – or for neglecting our fiduciary responsibility to nature or the future, which requires a "stewardship" paradigm as the operating principle – Brown [5] – or for equating economic efficiency with social good rather than recognizing that the "invisible hand" of the market system "disregards the moral and cultural problems raised by its concentration on individual self-interest and competitiveness and produces values which seem to over-reward greed, aggression and irresponsibility" – Jenkins [40, pp. 228–229]). Even though expanding on specific cost/benefit paradigm-challenging arguments such as these is beyond the scope of this discussion, it must be kept in mind, nonetheless, that when applying IAM results to actual decision-making these philosophical underpinnings of analytic methods do influence the outcomes – what has often been labeled as "framing" the problem in the sociology of scientific knowledge literature. To the extent that IAMs inform that value-laden process of decision-making, they can educate our intuitions and make our decisions "more rational". To the extent that, in a haze of analytic complexity, IAMs obscure values or make implicit cultural assumptions about how nature or society works (or the modelers' beliefs about how they "should" work), IAMs can thus diminish the openness of the decision-making process. And, to the extent that openness is proportional to rationality, diminished openness would render policy making even "less rational". I will conclude, in answer to the questions implicit in this article's subtitle, that both possibilities can and do occur, and will suggest ways to increase the likelihood that IAMs will inform more than they obscure.

2. Hierarchical development of IAMs in the climate change debate

I will shortly suggest a hierarchical approach to categorizing IAMs, but first wish to highlight the backdrop of multi-disciplinary tools upon which IA modelers draw, but which were created in various disciplines, primarily for purposes other than IA.

From multi- to inter-disciplinary. The "multidisciplinary tool kit" category in table 1 is not intended as a comprehensive listing, but is offered, nonetheless, to remind us of the contributions of many disciplines to the independent development of ideas or methods adopted by IA modelers to the global change assessment activity. Except for systems dynamics and, to a lesser extent, natural hazards and risk assessments, these tools are not very interdisciplinary.

I distinguish "inter" from "multi" disciplinary (e.g., Schneider [83]) in the sense that multidisciplinary implies ideas and methods from many disciplines brought to bear to help deal with a systems problem, but in which these

Table 1
Multidisciplinary tool kit development (still ongoing – and not primarily global change motivated).

• computing machines
• global observing systems
• numerical techniques for solving coupled sets of equations
• general circulation models (GCMs) of atmosphere and oceans
• sea ice and glacier models
• crop-weather models
• biogeographic models
• biogeochemical models
• ecosystem models
• demographic models
• macro economic models
• systems dynamics models
• natural hazards studies
• cultural theory
• risk and decision analyses
• opinion surveys
• ecophysiology
• ecosystems services concepts
• epidemiological methods
• non-market valuation
• GIS techniques
• technology diffusion/substitution models
• downscaling models to permit regional and local impact analyses from large-scale projections
• sociology of scientific knowledge

ideas and methods remain largely unintegrated, persisting primarily in their discipline of origin. "Interdisciplinary", on the other hand, implies an original *combination* of multidisciplinary ideas or methods that permits explanation or assessment not achievable by an unintegrated application of multidisciplinary ideas or tools. As a community of scholars, assessors and policy makers learn more about each of these initially unintegrated multidisciplinary contributions, such a community evolves towards being an interdisciplinary association (what has sometimes been labeled as an "epistemic" community, e.g., Haas [27]) capable of synergistically combining such knowledge into an original synthesis needed for IA. Edwards [15] has argued that climate models were the tool around which just such an epistemic community formed to address the climate change problem. However, as I have argued elsewhere (Schneider [85,87]), the process goes two ways: interdisciplinary analyses often uncover problems best addressed by disciplinary methods and traditions, which disciplinarians would not likely have discovered before the interdisciplinary project that identified this missing piece of disciplinary knowledge.

Clearly, as Parson [68] and others have noted, both multi and interdisciplinary developments are proceeding in parallel. Thus, fully integrated, comprehensive assessment of global climatic change issues is still not achievable. Nevertheless, by adopting more and better multidisciplinary ideas and tools into successive generations of increasingly integrated models, it is frequently assumed that greater realism can be attained, and thus increasingly useful insights can be added to the policy process dealing with climate change problems.

Hierarchy of IAMs and modeled components. Table 2 postulates five generations in the hierarchical development of IAM components and techniques as applied to climate change impact and policy analyses. Table 3 adds three cross-cutting categories – whose implementation need not wait for all preceding hierarchical steps to be completed – stressing predictability studies, validation and testing and incorporation of decision-makers into IAM activities. Table 2 is not intended to be fully comprehensive, nor is each level fully independent of others. It is offered to advance the process of categorizing the hierarchical nature of the development of IAMs, highlight the incorporation of various disciplinary tools – often developed for non-global change purposes – that IA modelers use (table 1), and to stress the need to develop protocols for evaluation and predictability studies (table 3) at every level. Moreover, it is not implied that all IAMs actually developed in the sequence outlined in table 2, nor that current IAMs which might incorporate features from third or even fourth generation models listed in the table necessarily include all of the features of earlier hierarchical categories. For example, a model that attempts to include biogeophysical surprise (e.g., ocean current flip flop) might not include endogenized technological change or stochastic variability. That is why I have not tried to characterize individual models by labeling them subjectively as examples of any one stage in the hierarchy. I perceive of most models as predominantly falling across one or two categories in table 2, with the bulk of current IAMs residing somewhere in the second and third generation categorizations. However, each such model would not likely include all features of those predominant categories. Moreover, each IAM could, at the same time, pioneer by incorporating a few aspects of later generation models.

The first generation IAM category in table 2 encompasses the methods, including modeling tools, used by initial greenhouse assessments – essentially consciousness raising exercises. In one such early self-labeled "integrated assessment", Schneider and Chen [90] simply calculated the cost of a scenario of sea level rise as the sum of the discounted lost property values in inundated areas, without depreciation, reinvestment, relocation or any other potential adaptations; nor were potential losses of historical or ecological significance quantified. Such refinements are placed in later generations in table 2.

In addition, a great deal can be learned from early assessments of other global change problems (e.g., supersonic transport impacts – Grobecker et al. [24]). Also instructive is the acid rain assessment experience (e.g., NAPAP [61], Alcamo et al. [2]), or energy systems analysis (e.g., CONAES [9]).

Table 2
Integrated assessment modeling of global climate changes: Hierarchy of climatic impact and policy assessment components.

I. Premethodological (essentially unintegrated) assessments
- climatic determinism (naive association of regional climatic and social factors)
- case studies in which climatic variations at a region are associated with environmental or societal "responses" (e.g., 1846 potato blight in Europe or 1970s Sahelian drought and its suspected impacts)
- direct cause and effect links without feedbacks (e.g., value of coastal damage made equal to inundated property market values with no adaptation)

II. Second generation (some integration) climatic impact and policy assessments
- $2 \times CO_2$ equilibrium snapshots (or simple time varying CO_2) GCM scenarios
- no aerosols or other heterogeneous radiative forcings
- no realistic transient climate change scenarios
- simple (or no) landscape changes
- simple (or no) endogenous adaptation/technological change
- time and space variations in climate and impact sectors assumed substitutable
- no stochastic variability of weather, economy or technology variables
- simple (or no) representation of non-market impacts
- may be multi-sector, multi-biome and multi-regional, but limited subsets of species, sectors or regions
- conventional discounting applied equally to impacts and mitigation costs
- simple (or no) representation of uncertainty via probability distributions

III. Third generation (partly integrated) climatic impact and policy assessments
- includes more realistic transient scenarios of heterogeneous radiative forcings driving coupled Earth systems models
- stochastic variability explicitly included
- adaptation/technological change endogenized
- land use changes (including urbanization) endogenized
- individual species and communities may be simply represented
- alternative discounting assumptions explored
- subjective opinions from decision analytic surveys endogenized and uncertainties explicitly treated via probability distributions

IV. Fourth generation (more integrated) climatic impact and policy assessments
- synergism among habitat fragmentation, exotic species invasions, chemical releases and climatic changes explicitly treated
- biodiversity and ecosystem services (i.e., "non-market" nature) endogenously treated
- plausible biogeophysical surprises explicitly considered
- alternative demographic, political and macroeconomic processes endogenously considered (i.e., inclusion of changes in human behavior at various levels)

V. Fifth generation (largely integrated) climatic impact and policy assessments
- changing value systems explicitly considered
- surprises to social systems and values explored

The bulk of formal climate assessment reports to date fit (somewhat uneasily) into the second and third generation categories (e.g., NAS [60], IPCC [37,38]), even though these studies are IAs (though they draw many of their insights from 2nd or 3rd generation IAMs) and they explicitly noted the potential importance of including issues such as stochastic variability or endogenous land use changes (attributes of later generation steps in the IAM hierarchy of table 2).

Some groups do include endogenous land changes (e.g., Alcamo [1]), but do not drive their models with realistic transient climate change scenarios since they use highly parameterized (e.g., zonally-averaged two-dimensional) climate models, even though they do project regional impacts. As noted, such hybridization of simple and more comprehensive models is a practical necessity given limited human, data and computing resources available to most groups of IA modelers (e.g., see also Prinn et al. [69]). Few modeling groups explicitly include "surprise" scenarios, although some models (e.g., Dowlatabadi and Kandlikar [13], Roughgarden and Schneider [80]) do formally treat uncer-

Table 3
Cross-cutting issues for IAMs of all generations.

- Predictability of integrated, multi-sector, multi-region, multi-species and multi-process models (including imaginable surprises) vigorously explored
- Validation and testing of model structure, output, input data and parameter values against other models and empirical data continuously practiced
- "Insights versus answers" debate highlighted via use of hierarchy of nested models. Decision-makers help to formulate and then incorporate IAMs into their decision-making calculus (i.e., "process is our most important product")

tainties via probability distributions whose outlier values are, in some sense, "imaginable surprises" (e.g., see discussion in Schneider et al. [95]).

The progressive generations offered in table 2 focus on how the elements and methods used in IAMs evolve, rather than how the IAs themselves developed, since the latter are harder to categorize in any simple hierarchical classification than IAMs. Nevertheless, the next section will broaden the discussion to IA of climate change issues, and weave the role of IAM into that larger context.

3. Guidelines for building and using IAMs in integrated assessments

Space does not permit an exhaustive catalogue of every imaginable strength and weakness of the IA paradigm for global change decision-making. Fortunately, several authors have attempted to diagnose and debate this topic in considerable depth (e.g., Rothman and Robinson [78], Parson [68], Rotmans and Van Asselt [79], Morgan and Dowlatabadi [56], Risbey et al. [73] – from which scores of additional and earlier references can be found), and here I will only briefly borrow some of their summary insights. For example, Wynne and Shackley [104] assert that IAMs are primarily tools for IA to use to generate insights into the decision-making process, not a "truth machine". Rotmans and Van Asselt [79], building on the "insights" theme, suggest that, depending upon which cultural view of development and nature one embraces, recommendations on how to respond to the prospect of global change disturbances will greatly differ. Risbey et al. [73] raise many issues, among them the value-laden analysis of the differential monetary value of human life, typically determined from the discrepancy between how much poor and rich societies are willing to invest to prevent the loss of a "statistical person". Although analytically convenient since this objective method permits risks to be put into a common metric (i.e., the dollar), it values the losses of poor countries from climatic damages that include loss of life much below (in absolute dollar terms) that of rich countries in an integrated assessment. (Similarly, social judgments are called for in arguing for any particular monetary value of a species threatened with extinction or a rapidly disappearing habitat type or a historical monument threatened with inundation.)

Risbey et al. [73] also note the difficulty in peer reviewing IAMs given the lack of an extensive interdisciplinary community experienced in working at the intersections of knowledge from the many sub-disciplines that comprise IA (see also Chen [6]). Parson [68] picks up on this theme of lack of interdisciplinary communities and adds the complication of incomplete disciplinary paradigms, noting, for example, that we "do not have general, causal, predictive theory of history, and neither building models, nor including sociologists, anthropologists, historians, and philosophers on assessment teams – though these are both good and important things to do – will give us one ... IA can reveal and characterize knowledge needs ... encourage thinking about whole systems ... and causal relations, ..., [but] puts you perpetually at risk of finding (or being offered) answers to them, and believing them – even for questions that cannot be answered, now or perhaps ever."

Model validation. I have often conceived of models as "teaching machines" that can help us to sort out relationships among many factors, but their credibility comes primarily from a combination of the reasonableness of their underlying structural assumptions and both heuristic and formal validation protocols. However, for complex nonlinear systems, intuitive or theoretical insights often follow, rather than precede model applications. Thus, to me, it is not very important whether such insights of necessity required or did not require model explorations to be uncovered, but rather that models are an integral component of the community process of exploring the character of complex systems. A number of observers, in the context of energy modeling a few decades ago, have argued that models can indeed provide insights, which, once provided, lead many analysts to believe the insights could have been attained even without the models. That is, such ideas simply stand on their own with the models primarily having served as a catalyst to discovery – or at least to more focused debate. For example, a large US assessment (Committee on Nuclear and Alternative Energy Systems – CONAES [9]) in the late 1970s was unable to reach much consensus about energy policy, despite the heavy use of models in specific applications. With no small measure of exasperation, this National Research Council committee confessed in its final report that "*there was sufficient disagreement among CONAES members about what was socially desirable and politically feasible to preclude the development of any 'most likely' or 'most desirable' scenario*". The numerical values were arrived at judgmentally and should not be regarded as the outcome of a complete chain of inference from a formal model and assumptions, although models were used as a partial guide to judgment" (CONAES [9, p. 567]). (This is an interesting example of the difference between a formal integrated assessment and IAMs.)

What is most germane for both the explanatory and policy purposes of models, I believe, is the need to *test the credibility* of their structural assumptions, input data, parameter values and outputs. In the context of complex systems for which confirming empirical evidence is difficult to obtain, or cannot be obtained prior to "performing the experiment" on the Earth system itself (Schneider [89]), then strictly speaking, "validation" is not possible in advance (Oreskes et al. [65]). But the term is still in widespread use, so even though I recognize the strict impossibility of before-the-fact validation of an IAM applied to the climate system problem, I will still use the term "validation" to imply the many kinds of testing strategies that can be used which provide, subjectively at least, credibility to the results and subsequent insights from IAMs.

I have previously distinguished several kinds of validation categories (e.g., Schneider and Londer [94]). First, detailed theoretical or observational studies of individual processes which are represented by model "parameterizations" (or "reduced form" equations in economic models) are needed to test individual structural elements. Second is overall model simulation skill – measured by aggregate model-derived state variables compared to empirical data (e.g., the ability of a climate model to reproduce deserts and rain forests in the right regions or the capacity of a crop yield model to simulate reasonably the yield difference between irrigated and unirrigated grains). Third, and perhaps most importantly, is the capacity of models to simulate the sensitivity of important state variables to exogenous changes like a volcanic eruption in a climate model or an oil price shock in an economic model. Such *sensitivity validation* exercises are essential before a climatic or economic model can be invoked to represent even partially credible estimates of the sensitivity of, for example, the climate to exogenous forcings like CO_2 increase or the costs to the economy of a carbon tax.

Finally, it is important to compare model results to empirical data at *the scale of the lowest resolved model elements*, not at the scale at which some empirical data may have been collected. For example, it is inappropriate to assert that a climate model which has 200 by 200 km resolution grid boxes should have its state variables compared against field data collected at point sites, unless many such sites are aggregated to provide a data set at the scale of the model's lowest resolved elements, or if it can be shown that such small scale data is, in fact, representative of the grid box average (e.g., see Root and Schneider [75]). In the same vein, some modelers also believe that a model is more credible to the extent it incorporates more known processes into its structure. Superficially, this would seem an obvious truism. However, not all processes at all scales are relevant to model variables at the scale of the lowest resolved element of the model. It is certainly true that cloud droplets, for example, may be important to precipitation processes, but it is not clear the extent to which they must be *explicitly* present in a global climate model, as their *effect* on larger scale phenomena is what is important to climate models. And it is virtually certain that inclusion of sub-atomic particles is wholly unnecessary – as well as impractical – in any foreseeable climate model! Lorenz [47], in the context of climate models, noted this difficulty:

> "In view of the manner in which mathematical models have evolved, and in view of our failure to have yet incorporated every feature which we *know* to be relevant, it is inconceivable that in the near future we shall construct a model possessing every feature which could possibly be relevant, i.e., which treats every not-strictly-constant feature of the atmosphere and its environment as a dependent variable. We therefore ought not to look upon a mathematical model as a means of by-passing the physical imagination needed to formulate hypotheses. We should, however, regard a model as a valuable tool for *testing* hypotheses. For this purpose, we can and must incorporate into our model each individual feature, such as variable sea ice or salinity, suspected of being important. Such testing seems essential if the hypotheses are not simply to remain hypotheses forever."

Therefore, the salient question for credibility of a model is the extent to which unresolved or neglected processes can be either ignored or their effects be adequately treated by parameterizations. Thus, testing the influence of such unresolved processes via reduced forms should be the object of validation exercises, not a catalogue of how many processes are included in an ostensibly "comprehensive" model independent of an evaluation of their importance to the model at the scale of its lowest resolved element.

Predictability limits. On a personal note, the above quote from Parson also reflects my long-standing – e.g., Land and Schneider [43], Schneider [84] – concern with the dearth of exploration of predictability limits for models of complex systems – point 1 in table 3 here. Liverman [45], for example, showed through use of a so-called "world model" (an advanced systems dynamics tool listed in table 1) that it was impossible to predict accurately the evolution of food prices, storage or trade, even if detailed regional and yearly crop yield information were specified (rather than predicted) because of unpredictable political events such as the OPEC oil embargo's effect on energy prices in 1974 or the USSR's decision in 1972 to massively buy grain on the world market. Despite the likely unpredictability of such salient political "surprises", precision in model forecasts is not hopeless (e.g., Land and Schneider [43]), though, because such coupled models can be used for *sensitivity analyses* of how certain policies (size of and access to food stocks, for instance) can reduce the risks of a number of plausible – but probably unpredictable – events, like a drop in fertilizer availability from surprise energy price shocks.

I do not thus restrict the definition of "predictability" to mean only a reliable forecast of a single time series of some state variables. Such a strict definition would find few state variables of complex systems enjoying much "predictability". Accuracy in the time evolving projection of a multi-component IAM would very likely degrade as unpredictable events – exogenous or endogenous – occurred. However, a forecast of the sensitivity of the system to specific exogenous factors, for example, could be precise even if many unpredictable events caused the system variables to drift from its projected state. In other words, the system might be predictably different from what it otherwise would have been because of the well modeled response to an exogenous factor even if the absolute state of the system over time is largely unpredictable.

Clearly, as the above examples suggest, a great deal can be learned and useful projections of the sensitivity of a system to specific disturbances made even when individual realizations (i.e., a single time series of state variables) may have no reliable predictability. By analogy, even though no individual weather events can be reliably predicted past a week or two (Lorenz [48]) owing to the chaotic internal dynamics of the atmosphere, the effects of a volcanic dust veil on the climate of the few years following the eruption are likely to be highly predictable. Prediction of the relative importance of different physical, biological or social factors on the behavior of other variables of interest can still be of both scientific or societal utility.

Of course, we currently have a much more developed conception of boundary condition changes that could plausibly disturb the climatic system than the social systems. Nevertheless, my point in the above examples of unpredictability is not to discourage coupled model experimentation, but instead to emphasize that the stress should be put on identifying which limited subsets of the comprehensive coupled Earth system (pictured by typical, complex box and arrow systems diagrams) have the best likelihood of limited predictability – even if we do not now know how (or may never be able) to predict accurately the overall coupled system behavior well. In addition, we need to focus on which social and environmental sub-systems are most sensitive to global change disturbances. Then, knowing both what needs to be known and what is most likely to be able to be understood and reliably projected leads us to subsets of complex systems diagrams upon which we can focus extra efforts (e.g., Schneider [84]).

Of course, as integrated assessment models incorporate coupled climate, ecology and societal sub-models, it is likely to be tougher to provide credible projections of state variables in the IA context than for any individual sub-discipline like climate modeling. Modelers must therefore be aware of the danger of "lamp-posting", which is Ravetz's [70] term for the cliché that warns of the tendency to look for a lost set of keys under the lighted lamppost, rather than in the dark field where they were probably dropped. Salience must compete with tractability in model design, which is one reason why it is critical to involve model users, most notably decision-makers, at very early stages of model design, a point stressed in table 3.

Policy utility. Parson [68] also addresses the question of policy utility of IAMs, noting that "there is much persuasive force to the rationalist intuition that even uncertain or partial scientific knowledge *should* be able to help inform policy choice. But the manifest weakness of such results makes them highly vulnerable to various forms of partisan exploitation and attack, as well as sincere misinterpretation." His solution, reflected by nearly all who advocate use of IAMs, is "increased involvement of diverse policy actors in the development and use of assessments and assessment tools ..." (see also, Parson [67]). Robinson [74] has, likewise, argued for using social agents to make behavioral choices extend to the model, but which help to determine scenarios within the model.

Who could disagree? But how do we cajole such a diverse set of policy actors and social agents to put aside their agendas, prejudices and fears to even look at complex analytical tools like IAMs? Moreover, how can we help them to overcome the initial effort barrier to their getting started in discovering – and using – IAMs? We, who develop and debate IAMs, will need to do more than note this dilemma as a standard caveat in our professional presentations (Ravetz [70]). I believe we each need to schedule fractions of our time to become active participants in the process of entraining as many diverse policy actors as we can talk into to trying out our wares (hard and soft). Decision-maker participation in IAM activities – from conception to use – simply will not happen by chance. We have to work hard at outreach to the decision-making community and to relentlessly strive to sustain their interest – even in the face of the lack of incentives in academic institutions to engage in such outreach activities (e.g., Schneider [87]).

Assessments are not disciplines. Morgan and Dowlatabadi [56], agreeing that "doing integrated assessment will typically not be 'answers' to specific policy questions ...", proposed seven "basic principles" to guide all integrated assessments. They are reproduced here as table 4. To their seven I would add two more. First, their point 2 should be expanded to include formal, periodic international "rolling reassessment" (e.g., IPCC-like re-assessment reports appearing every 5–10 years) to encourage more adaptive management (e.g., see Lempert et al. [44]) and to minimize costs from actions or inaction based on early-generation IAM results which later on appear erroneous. Second, following from the earlier discussion about incorporating decision-makers into the IA process, I would add a point 9 in table 4: put decision-makers in front of the computer screen and bring them (or their designees) into all phases of IAM development and use, especially helping IA modelers to ask the right policy questions of their tools – and to push IA modelers to modify their designs so as to be able to address such directed questions. The incorporation of decision-makers at the early stages of IAM design is an example of how the IA process (what is addressed in table 4) differs in principle from many discipline-directed tools development activities (the focus of table 1), since scientific disciplines are – or at least strive to be – "curiosity driven" associations primarily in search of explanations of natural and social phenomena rather than policy-oriented knowledge gatherers whose tools' very designs are policy-driven or forecast-oriented. Of course, as argued earlier, many disciplinary discoveries and tools need to be swept into the IA process (tables 1 and 2), and IAMs also can have purely explanatory applications to complex systems analysis. Nevertheless, the policy-orientation of IA at the outset requires explicit acknowledgment and care in the design and applications of IAMs.

However, even though the practice of interdisciplinary integration via integrated assessment may initially involve inputs from many formally constituted disciplines, after an interdisciplinary community becomes familiar with these concepts and teaches them to succeeding generations of IA modelers, then it is conceivable that a new discipline

Table 4
Seven attributes which Morgan and Dowlatabadi [56] believe are the hallmarks of a good integrated assessment of climate change.

1. The characterization and analysis of uncertainty should be a central focus of all assessments.
2. The approach should be iterative. The focus of attention should be permitted to shift over time depending on what has been learned and which parts of the problem are found to be critical to answer the questions being asked.
3. Parts of the problem about which we have little knowledge must not be ignored. Order-of-magnitude analysis, bounding analysis, and carefully elicited expert judgment should be used when formal models are not possible.
4. Treatment of values should be explicit, and when possible parametric, so that many different actors can all make use of results from the same assessment.
5. To provide proper perspective, climate impacts should be placed in the context of other natural and human background stochastic variation and secular trends. Where possible, relevant historical data should be used.
6. A successful assessment is likely to consist of a set of coordinated analyses that span the problem ... not a single model. Different parts of this set will probably need to adopt different analytical strategies.
7. There should be multiple assessments.
   - Different actors and problems will require different formulations; and
   - No one project will get everything right. Nor are results from any one project likely to be persuasive on their own.

could eventually emerge. Of course such an evolved new discipline will not be long viable if it does not continually entrain the latest data, ideas and methods from the traditional disciplines, so I suspect that even as IA may move towards its own eventual "discipline-like" set of methods and measurements, it will always be striving to become more interdisciplinary.

One interesting perspective on the disciplinary likeness of IA has been suggested informally by Carlo Jaeger (personal communication): "economics does not enter the IA process on a par with other specialized disciplines in need of some integrative process, but as the framework which at least allegedly is required for such integration. If this is right, then IA will end as a sub-discipline of economics; if it is fallacious, the possibility, but also the need, for serious advances in economic theory arises." In particular, he cites the need to explore the implications of threshold phenomena and the consequent possibility of multiple economic equilibria (see, e.g., Jaeger and Kasemir [39]). If they occurred, such threshold phenomena could cause counter-intuitive associations, such as increasing non-conventional energy production even if conventional energy prices were not rising, Jaeger and Kasemir suggest. "These research opportunities", Jaeger continues, "can attract gifted researchers and make the IA community even more exciting than it already is". Despite this intriguing caveat on the possibility of multiple equilibria, most of what follows remains in the one-equilibrium economy paradigm. This possible limitation will not inhibit the raising of so many open questions that IA researchers can likely remain quite productively busy refining their tools for the foreseeable future, even within this conventional paradigm.

To focus and build on the above discussions, I will single out several policy-relevant topics to illustrate where IAMs need much more attention and why their "answers" should rarely be taken literally, even though their implications may be taken seriously – if the assumptions that frame the assessments are both plausible and appreciated by users.

4. Examples of problematic topics for IAM applications

Although many specific and general topic areas could be selected to exemplify the problems IA modelers still face in improving their tools, I will raise three types of problems that are difficult, but I believe necessary, for IAMs to address. These include (1) how to add processes to an IAM that most agree should be added but nobody knows how to do well; (2) how to make structural modifications to IAMs to better incorporate transient effects, surprises and probabilistic (including subjective) data; (3) how to orient IAMs to deal more transparently with current policy questions.

4.1. Problematic but essential processes that need to be included in IAMs

4.1.1. Induced technological change (ITC)

The costs to the global economy of carbon abatement policies depend dramatically on the rate of technological improvements in non-fossil fuel powered (so called "non-conventional") energy supply systems and the rate of improvement of energy end use efficiency. The Stanford Energy Modeling Forum (EMF-12) compared the costs to the economy of a given carbon tax for a standard case and one with "accelerated technologies" in which non-conventional energy systems and greater efficiency in general are available sooner and cheaper, and concluded that tremendous reductions in the costs of carbon dioxide emissions abatement could be enjoyed if technological development was accelerated (e.g., Gaskins and Weyant [18]). The EMF-12 studies also showed that the emissions paths and costs of abatement depend directly on the rate of energy efficiency improvements (so called AEEI – the "autonomous energy efficiency improvement" parameter – typically around 0.5–1% per year).

However, in the actual economy neither the cost of non-conventional energy supply systems nor the rate of energy efficiency improvements (EEI) are fully "autonomous" –

i.e., varying only with time, thus are exogenous to the economic system simulated by the EMF study authors' models. On the contrary, as Grubb et al. [26] have argued, EEI should not only be autonomous, but also endogenous to the system. Standard economic theory would suggest that the price of non-conventional energy, or the rate of EEI, would both be favorably adjusted as conventional energy prices increased, the latter a function of carbon abatement policies like a carbon tax. (Not to endogenize technology change as a function of carbon policies in economic models is analogous to climate models making cloudiness change vary exogenously with time rather than endogenously with, say, internally calculated humidity and atmosphere stability – the so-called "cloud feedback" problem, IPCC [36].)

Similarly, a climate policy such as a subsidy to non-conventional energy research and development (R&D) would also accelerate EEI or decrease the long-term price of non-conventional energy beneath its projected baseline path. By allowing energy R&D to compete with other economic sectors in a highly aggregated general equilibrium model of the US economy, Goulder and Schneider [23] postulate that a noticeable carbon tax would likely dramatically redistribute energy R&D investments from conventional to non-conventional sectors, thereby producing induced technological changes (ITC) that lower long-term abatement costs. Unfortunately, most integrated assessment models to date do not include any endogenous ITC formulation (or if they do, it is included in a very *ad hoc* manner), and thus such IAM insights about the costs or timing of abatement policies would be very tentative. However, even simple treatments of ITC (e.g., Grubb et al. [26], Goulder and Schneider [23], Dowlatabadi [14], Goulder and Mathai [22], Nakicenovic [59]) can provide qualitative insights that can inform the policy-making process, *provided* the results of individual model runs are not taken literally given the still-*ad hoc* nature of the assumptions that underlie endogenous treatments of ITC in IAMs (or at least the economic components of IAMs).

To make this statement more concrete, I will first briefly summarize a calculation Goulder and Schneider [23] (hereafter GS) recently made using a simplified general equilibrium model to investigate the implications of ITC on the costs of a specified carbon tax, with the costs of investments in R&D explicitly recognized. Thus, even if a carbon tax were to induce increased investment in non-carbon based energy systems (which, indeed, does happen in our simulations), the opportunity costs of investing in non-carbon technologies, which may crowd out investments in conventional R&D, impact on the costs to the economy of any specific abatement pathway. I will provide a few more details of the GS ITC study to exemplify the kinds of assumptions that policy-makers need to be aware of in interpreting IAM results with or without reduced form treatments of ITC.

GS have, as noted, developed analytical and numerical general equilibrium models to investigate the significance of induced technological change for the attractiveness of CO_2 abatement policies in the context of the U.S. economy (I believe that the basic principles can be well demonstrated by the U.S. case, even though I recognize any quantitative results are not general – especially for countries with structurally different economic and political systems). Each model characterizes technological change as a result of optimizing decisions to invest in various R&D sectors of the economy.

ITC, as GS modeled it, implies that the gross costs (i.e., the costs before accounting for environment-related benefits of abated CO_2) of a specified carbon tax are higher than they would otherwise be if there were no ITC (assuming that all prior inefficiencies in R&D markets are absent). This result, which appears to be in contradiction with earlier studies of ITC (e.g., Grubb et al. [26]), comes about because of the explicit inclusion in GS of the opportunity costs of R&D. However, if there were serious prior inefficiencies in R&D markets such that the marginal benefits of R&D is much higher in alternative energy sectors than in conventional, carbon-based sectors, then ITC can imply lower gross costs than would occur in its absence. (All of this neglects historic inequities in which past subsidies to conventional energy have given it an "unfair" competitive boost.) Or, if R&D markets under-invest in knowledge generation for fear that some of their investment will "spill over" to every competitor (a social good, but a disincentive to individual investors who wish to keep their discoveries private), this R&D market failure suggests that R&D subsidies to correct the market failure would be economically efficient (Schneider and Goulder [92]). However, for the idealized assumptions of (1) perfectly functioning R&D markets and (2) a scarcity of knowledge-generating resources (e.g., all capable engineers already fully employed) at the time the carbon tax is imposed, the presence of ITC appears not able by itself to make carbon abatement become a zero cost option, and in the GS model can actually increase the gross costs to the economy of any specific, given carbon tax.

However, not in contradiction, but in support of previous studies on ITC (Grubb et al. [26], Dowlatabadi [14]), GS show that even when ITC as modeled gives rise to higher *gross* costs of a given carbon tax, ITC still raises the attractiveness of CO_2 abatement policies by reducing the costs to the economy *per unit* CO_2 *abated*. That is, since the carbon tax, for example, induces more investment in R&D knowledge generation in non-conventional energy industries, this leads to more rapid discoveries which lower the costs of future energy services generated by non-conventional energy systems. Thus, more abatement can be brought about per unit carbon tax with ITC than without ITC. Put another way, the benefits in the form of averted climate damages from augmented abatement could more than compensate for the higher gross costs of ITC. Alternatively, a given abatement target could be reached at lower costs (e.g., a lower value of carbon tax) because of ITC.

Many caveats are needed: (1) questionable generality of the U.S. economy-oriented GS model for non-developed country economies, (2) the returns on investment in energy R&D in GS are based on data from a past decade which might not be valid very far into the future, (3) what is the extent to which R&D knowledge-generators (e.g., underemployed or not-yet-trained engineers) can be quickly made available to non-conventional energy sectors so that the opportunity costs of a redeployment of technologists from conventional energy sectors would be lessened, (4) the degree and kinds of R&D market failures present can radically alter the conclusions relative to a perfectly functioning R&D markets assumption, (5) the possibility of multiple equilibria in which the quantity of energy provided may or may not be price sensitive during transitions to alternative equilibrium states, and (6) even the very paradigm of maximizing utility or consumption inherent in the general equilibrium model cost/benefit optimizing approach can all be challenged on technical and philosophical grounds. Nevertheless, I believe the added insights this early type of ITC analysis brings to the IA of climatic change policy options are instructive – provided users of these model results are aware of the many technical and philosophical assumptions such as (1)–(6) above.

4.1.2. Adaptation

One of the major differences in estimates of climatic impacts across different studies is how the impact assessment model treats the adaptation of the sector under study (e.g., coastline retreat, agriculture, forestry, etc.). For example, it had often been assumed that agriculture is the most vulnerable economic market sector to climate change. For decades agronomists had calculated potential changes to crop yields from various climate change scenarios, suggesting some regions now too hot would sustain heavy losses from warming whereas others, now too cold, could gain (e.g., see references in Rosenzweig et al. [77] or Smith and Tirpak [97]). But Norman Rosenberg (e.g., Rosenberg and Scott [76]) has long argued that such agricultural impact studies implicitly invoked the "dumb farmer assumption". That is, they neglected the fact that farmers are not "dumb" and do adapt to changing market, technology and climatic conditions. Agricultural economists like John Reilly (e.g., see [37, chapter 13] of which he is primary author) believe that such adaptations will dramatically reduce the climate impact costs to market sectors like farming, transportation, coastal protection or energy use. Ecologists, however, often dispute this optimism since it neglects such real world problems as people's resistance to trying unfamiliar practices, problems with new technologies, unexpected pest outbreaks (e.g., Ehrlich et al. [17]), or the high degree of natural variability of weather (Schneider [88]), which will mask the slowly-evolving human-induced climatic signal and discourage farmers from risking anticipatory adaptation strategies based on climate model projections.

Several years ago I was engaged in a debate at an EMF workshop with one agricultural economist who asserted that modern farmers could overcome virtually *any* plausible climatic change scenario. I countered that he conceived of these farmers as all plugged into the electronic superhighway in real time, aware of the probability distributions of integrated assessments and financially and intellectually capable of instant response to a bewildering array of changing pest, crop, weather, technology, policy and long-term climatic conditions. He simply replaced the unrealistic "dumb farmer" assumption of the past, I countered, with the equally unrealistic "genius farmer". Rothman and Robinson [78, p. 30], in a conceptual synthesis of IA, contrasted the "dumb farmer" to a "clairvoyant farmer", and, borrowing from Smit et al. [96], suggest that "the next step in the evolution of IAs is to assume a 'realistic farmer' ". Real farmers, I agree, are likely to fall somewhere between. And, especially in developing countries, problems with agricultural pests, extreme weather events and lack of capital to invest in adaptive strategies and infrastructure will be a serious impediment to reducing climatic impacts on agriculture for a long time, even for a "genius farmer" or one possessed with clairvoyance.

Adaptation is seriously challenged by the very noisy nature of the climatic system. It is doubtful that those in agriculture or concerned about coastline retreat will invest heavily in order to adapt their practices so as to follow before-the-fact climate model projections, rather than actual events. The high natural variability of climate will likely mask any slowly evolving anthropogenically induced trends and impacts – real or forecast. Therefore, adaptations to slowly evolving trends embedded in a noisy background of inherent variability are likely to be delayed by decades behind the slowly evolving global change trends (e.g., Schneider [88], Morgan and Dowlatabadi [56]). It is doubtful that millions of disaggregated decision-makers (farmers in this example) will respond uniformly or quickly to forecasts of global climatic changes from IAMs. On the other hand, one of the technological adaptations that could mitigate climatic impacts on agriculture is seed development to cope with altered climates. And since there is but a small number of seed companies capable of altering the genetic character of crops and marketing these better-adapted strains on a large scale to farmers (in OECD-like countries at least), then rather than millions of disaggregated decision-makers involved here, perhaps the more appropriate number is three or four orders of magnitude smaller. In essence, the problem in modeling adaptation rests on how to incorporate human behavior into the models' structure (perhaps in menu options) so as to make the models more "actor-oriented". Decision-makers who turn to IAMs to help inform them about the costs of climate change must be aware of the controversial nature of assumptions about adaptation behavior of various actors which often lurk invisibly in different IA studies.

Furthermore, there is an additional problem decision-makers must be aware of with conventional economic analyses of the potential impacts of climate change on market sectors like agriculture or coastline change: the prospect of winners and losers. The field of "welfare economics" calculates net changes to overall (not individual) economic welfare of various activities and events, and such costs and benefits from the climate change estimates are used in integrated assessments. Thus, if Iowa farmers were to lose one billion dollars from reduced corn yields associated with warming, but Minnesota farmers simultaneously gained a billion dollars from longer growing seasons, then net U.S. economic efficiency change would be zero. But this hardly constitutes a neutral impact in terms of "welfare", as the political impacts could be substantial: for example, there could be demands for compensation from the "winners" to the "losers". This entire question of "redistribution costs" has so far been minimal in the climatic impact assessment debate, but certainly will not go unnoticed in the political arena, as Rotmans and Van Asselt [79] also argue.

4.1.3. "Ergodic economics"

In addition to underlying assumptions about adaptation determining to a large degree the impacts that specific climatic change scenarios are predicted to have on agriculture, coastlines or forestry, the many interacting factors across connected physical, biological, and social sub-components of the Earth system – the combination of which are the focus of IA modeling – present a daunting challenge. Therefore, some analysts (e.g., Mendelsohn et al. [53]) have suggested a shortcut around the attempt to explicitly model the salient complex interacting processes by letting the actual system try to answer the question of how it would respond to climate change (e.g., how yields would change, adaptation responses, etc.). Climatic model simulations for CO_2-induced climate changes are used to determine regional annual temperature and precipitation changes, which are "combined with sectoral information for agriculture, forestry, coastal resources, energy and tourism, via a set of sectoral climate-response functions" to calculate market damages "for each of nearly 200 countries" (Mendelsohn et al. [52]). Numerical values of these damages (typically net market benefits in cold regions and net costs in warm places) are given in tables to two or more significant figures. As the authors explain, the response functions which determine the "answers" are based on cross sectional studies which:

> "examine how firms and people adjust their behavior to accommodate local climate, the resulting response functions integrate human adaptation. A separate response function is estimated for agriculture, forestry, coastal resources, commercial energy, residential energy, and tourism. The effect of a temperature change in the response function depends on the initial temperature. If a country begins with a cool temperature, a slight warming will result in benefits. If a country begins with a warm temperature, increased warming is strictly harmful.
>
> The response functions describe net revenue in each sector given climatic and economic conditions. To evaluate the welfare impact of a climate change, the net revenue before and after the change must be compared" (Mendelsohn et al. [52]).

The authors, noting the potential divisiveness in widely differing market sector costs and benefits of climate change to various countries found by using their assumptions and methods, suggest that these model results, "may make international agreement on climate-change policy more problematic".

To me, what is at most "problematic" in this analysis was not the results, but the likelihood that many users of these results may not be aware of the many fundamental assumptions invoked both implicitly and explicitly by the use of this one of the techniques in the study (the so-called "hedonic" method), assumptions not universally lauded, not always transparent, and for which plausible alternatives could radically change the "answer".

In brief, rather than account explicitly via a process-based systems model for complex, coupled physical, biological, and social dynamics that determine the profitability of agriculture or forestry, the hedonic method simply compares these bio-economic activities in warm places like the U.S. Southeast and colder places like the Northeast. This spatial difference in climate provides a proxy for how temperature changes in each place might affect these segments of the bio-economy. The method is controversial, since natural scientists often dispute that the difference between business as usual in northern climates or southern climates (i.e., two different regions) can act as a proxy of impacts in one region from time-evolving or transient changes in temperature and other variables, to say nothing about surprises. In essence, these methods assume a perfect substitutability for changes at one place over time with changes across space at the same time – a debatable assumption that is tantamount to the *ergodic hypothesis* in mathematical statistics.

A system is "ergodic" if an ensemble of replicates averaged at one instant of time produces the same statistical results as an infinite time average of one member of the ensemble. In statistical mechanics this would mean that an infinite time average of the varying speed of one molecule in an isolated enclosure produced the same value (of kinetic temperature) as the instantaneous average of all the molecules in the container. "Time and space" in this example are, in essence, substitutable – the system is ergodic. Of course, this result will only occur if the system has a unique steady-state response to any exogenous forcing. In other words, an ergodic system's single equilibrium state has no memory of its evolutionary path, only its boundary conditions; i.e., it is a "transitive" system (e.g., Lorenz [46,47]).

The basic rationale for what I am calling by analogy "ergodic economics", is that process-based simulation models, no matter how complex are, nonetheless, still very "dumb" relative to real natural/social systems. Therefore, why not let the actual system reveal its sensitivities/preferences and adaptive potential over time to global change disturbances in one place by empirically determining how the real world has responded to "global-change-like" disturbances at one time in different places. However, the reliability of the hedonic method rests on three quite fundamental assumptions that need to be explicit in the minds of potential users of the results before they let this method provide policy advice on the viability of adaptation, for instance. The three assumptions are:

1. *Ergodic economic substitutability*: Variations over time and space are equivalent (e.g., long-term averaged climate and/or economic differences between two separate places are equivalent to changes of comparable magnitude occurring over time in one place).
2. *Transitivity*: Only one steady state occurs per set of exogenous conditions (i.e., the same path independent, long-term impacts occur for all possible transient scenarios). In other words, surprises and synergisms, which are non-linear and likely to depend on the path of system changes, pose no qualitative threats to credibility of the results.
3. *Higher moments are invariant*: A primary variable used to compare two separate regions climatically is annually averaged surface temperature. Thus, a 5°C difference across two spatial areas is used to predict a response to a 5°C warming occurring over time at the colder area. This modulus of difference, annual mean surface temperature, may not be a good proxy for actual climatic changes occurring over time – including all higher moments such as daily or seasonal variability (see, e.g., Mearns et al. [50] or Overpeck et al. [66], the latter for a paleo-climatic example of "no-analog" climate conditions). For example, if most of the warming occurred at night (as some climate models project), this would have very different ecological or agricultural impacts than if there were no change in the diurnal cycle. Or, if seasonality were altered, then even the same annual surface air temperature difference today across space would likely be a poor analogy for the impact over time. Or, if between now and a specified future time, precipitation increased by ten percent, but more than half this annually averaged increase were distributed in the top decile of rainfall intensity (as it has in the U.S. since 1910 – Karl and Knight [42]), then using annual precipitation (let alone annual temperature!) difference between two regions today as a proxy for the impacts of a ten percent precipitation increase in the future in the drier location would likely be a very poor representation of what would happen, even given the same annually averaged difference.

Clearly, these three assumptions are not valid for many IA applications. But the point here is not to dispute the conclusions published to date based on hedonic methods, only to highlight the implicit assumptions. More specifically, the prime finding with the hedonic method used by Mendelsohn et al. [52], as already noted, is that more heat will make already hot places poorer and currently cold places richer. Countries like Canada win and India lose – a sort of "neo-climatic determinism" reminiscent of that espoused at Yale University by Ellsworth Huntington eighty years ago. Mendelsohn and colleagues wisely acknowledge that even if their conclusions were that the rich countries with big economies and colder locations win more economically than poorer countries that typically are in hot climates lose, this is not a conflict-free scenario, particularly since the standard economic evaluation (so-called willingness-to-pay) for the "value" of a statistical human life in rich countries is ten or more times greater than for citizens of poor countries.

None of the concerns raised in this section is designed to suggest that it is inappropriate to include hedonic methods in the spectrum of other partially integrated assessment techniques that currently impinge on the policy debate. On the contrary, they inform one's intuition about possible market-variable impacts of certain climate changes under specified assumptions. My purpose here is to exemplify the critical need for producers and users of any IA products to open and conclude their presentations with clear statements about the assumptions and uncertainties in the methods, and not to overload the presentation with stand-alone, caveat-free, multi-decimal place tables or results that can be easily over-interpreted by uninformed users. Later on I will argue that, at the least ranges or, better, probability distributions, are more faithful representatives of the insights one might properly draw from most IAMs, than are several significant figure entries in "best guess" tables.

4.2. Structural modifications to IAMs to incorporate transients, surprises and (subjective) probability analyses

4.2.1. Transients

One element of IAMs is a numerical model of the Earth's climate capable of simulating the climatic response to scenarios of altered CO_2 and other radiatively active trace constituents of the atmosphere that are known to be changing from human activities – so-called "global change radiative forcings".

Until recently, climate modeling groups did not have access to sufficient computing power to routinely calculate time evolving runs of climatic change given several alternative future histories of greenhouse gases and aerosol concentrations. That is, they did not perform so-called "transient climate change scenarios". (Of course, the real Earth is undergoing a transient "experiment" – Schneider [86].) Rather, the models typically estimated how the Earth's climate would eventually look (i.e., after a long-term transition to equilibrium) after CO_2 was artificially doubled and held fixed indefinitely rather than increased incrementally over time as it has in reality or in more realistic transient model scenarios.

Transient model simulations exhibit less immediate warming than equilibrium simulations because of the slowly building radiative forcings combined with the high heat holding capacity of the thermally massive oceans. In other words, some of the warming is not realized immediately (e.g., Hansen et al. [30]). However, that unrealized warming eventually expresses itself many decades later. This thermal delay, which can lull us into underestimating the long-term amount of climate change, is now being accounted for by coupling models of the atmosphere to models of the oceans, ice, soils, and biosphere (so-called Earth system models – ESMs – which are essential components of any IAM effort). Early generations of such transient calculations with ESMs give much better agreement with observed climate changes on Earth. When the transient models at the Hadley Center in the United Kingdom (Mitchell et al. [54]) and the Max Planck Institute in Hamburg, Germany (Hasselmann et al. [32]), were also driven by both greenhouse gases and sulfate aerosols, these time evolving simulations yielded much more realistic fingerprints of human effects on climate (e.g., Santer et al. [81]). More such computer simulations are needed (e.g., Haywood et al. [33]) to provide greater confidence in the models, but many more scientists are now beginning to express growing confidence in current projections [36, chapter 8].

One current problem with such transient coupled ESMs needed for regional impact assessment efforts is the great complexity of each sub-model, which creates a significant burden for data requirements, computational resources and validation possibilities. Practical considerations typically prohibit the coupling of a large number of very highly spatially resolved models of atmosphere, oceans, ice or biota to be run in transient mode over centuries of simulated time. Therefore, modelers often use highly parameterized (or reduced form) models to allow practical computations given limited resources (e.g., see Root and Schneider [75]). Downscaling (e.g., Mearns [51]) or hybridization across vastly different spatial scales of highly resolved and highly parameterized models for special purposes will be a fundamental feature of climatic impact assessment for the foreseeable future (e.g., as done by Schlesinger [82] for the EMF-14 study). Therefore, there will be a continuous need for protocols to evaluate the credibility of such hybridized modeling systems.

Some of the validation protocols could, as noted earlier, include: (1) inter-comparisons of highly aggregated models with a limited set of highly resolved test runs or special field experiments, (2) inter-comparisons of such hybrid models with different designs against each other, (3) tests of the ability of such models' simulations to capture known and salient features of the actual natural/social systems, and (e.g.) the ability of all models to demonstrate reasonable sensitivity responses to known forcing events (e.g., physical sub-models should respond reasonably to volcanic dust veils or changes in the Earth's orbital elements and the impact of price shocks or trade policy changes on societal models should bear resemblance to actual societal impacts).

4.2.2. Surprises

Even the most comprehensive models of such a very complicated coupled system like an ESM are likely to have unanticipated results when forced to change very rapidly by external disturbances like CO_2 and aerosols. Indeed, some of the transient coupled atmosphere–ocean models run out for hundreds of years exhibit dramatic change to the basic climate state (e.g., radical change in global ocean currents – see Manabe and Stouffer [49] or Haywood [33]). More recently, Stocker and Schmittner [98] have argued that rapid alterations to oceanic currents could be induced by faster forcing rates.

Thompson and Schneider [99] used very simplified transient models to investigate the question of whether the time evolving patterns of climate change might depend on the rate at which CO_2 concentrations increased. For slowly increasing CO_2 buildup scenarios, the model predicted the standard model outcome: the temperature at the poles warmed more than the tropics. Any changes in equator-to-pole temperature difference help to create altered regional climates, since temperature differences influence large-scale atmospheric wind and ocean current patterns. However, for very rapid increases in CO_2 concentrations Thompson and Schneider [99] found a reversal of the equator-to-pole difference occurred in the Southern hemisphere. If sustained over time, this would imply unexpected climatic conditions during the century or so the climate adjusts toward its new equilibrium state. In other words, the faster and harder we push on nature, the greater the chances for surprises – some of which are likely to be damaging.

Fifteen years later, the IPCC [36, p. 7] concluded its Summary for Policymakers with the following paragraph:

> Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises". In particular these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behavior. Progress can be made by investigating non-linear processes and subcomponents of the climatic system. Examples of such non-linear behavior include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

Of course, the system would be less "rapidly forced" if decision-makers chose as a matter of policy to slow down the rate at which human activities modify the atmosphere. To deal with such questions the policy community needs to understand both the potential for surprises and how difficult it is for IAMs to credibly evaluate the probabilities of currently imaginable "surprises", let alone those not currently envisioned (e.g., see Schneider et al. [95]).

This discussion of transients and surprises can be connected to the earlier discussion of the third assumption inherent in "ergodic economics": invariance of higher moments. Clearly, rapid transients or non-linear events are likely to cause higher statistical moments of the climate, as well as environmental or societal impacts, to be quite different from those that would occur with smoother, slower changes. Thus, transitivity of the Earth system – i.e., a path independent response, the second "ergodic economics" assumption – is indeed debatable.

4.2.3. Adding subjective experts and belief systems via probability distributions

Nordhaus [62], in a pioneering study, calculated the "optimal" carbon tax to accompany a climate change scenario and its assumed climate damage (about 1% of GDP in the next century). Critics charged that this damage estimate underestimated impacts on non-market amenities (like security or biodiversity), or ignored implications if there were surprises.

To his credit, Nordhaus reacted to his critics by conducting a survey of a broad spectrum of opinions as to the value of damages – market and non-market – from hypothesized global warming scenarios (Nordhaus [63]). He recognized that it is difficult to value so-called "non-market" sectors such as the value of lost species, value of lost wetlands from sea level rise, or the costs from conflicts that might be induced by the creation of "environmental refugees" (Myers [57]) or any of the other non-market amenities. Since these defy simple quantitative treatment, he took an alternative approach – to use decision analytic techniques and to sample the opinions of a wide range of experts who have looked at climatic impacts and asked them to provide their subjective probabilities as to what they thought the costs to the world economy would be from several climate warming scenarios.

The numbers themselves are not what is so interesting, but rather the cultural divide across natural and social scientists that his study revealed, a result for an expert community that could, at least partly, be anticipated by Douglas and Wildavsky's cultural theory [12]. Nordhaus sampled the opinions of classical economists, environmental economists, atmospheric scientists, and ecologists. The most striking difference in the study was that the social scientists – conventional economists predominantly – virtually as a group, considered even radical a scenario in which a 6°C warming would unfold by the end of the next century (a scenario I would label as catastrophic, but improbable – maybe only a 10 percent chance of occurring – see Morgan and Keith [55]) as not very catastrophic economically. Although they expressed a wide range of uncertainty, most conventional economists still thought even this gargantuan climatic change – equivalent to the scale of change from an ice age to an inter-glacial epoch in a hundred, rather than thousands of years – would likely (their 50th percentile estimate) have only a several percent impact on the world economy in 2100. In essence, they accept the paradigm that society is almost independent of nature. In their opinion, most natural services (e.g., Daily [11]) associated with current climate are either not likely to be significantly altered or could be substituted for with only modest harm to the economy.

On the other hand, the group Nordhaus labeled as "natural scientists" thought the damages to the economy (including non-market components) from the severe climate change scenario would range from no less than several percent lost up to 100 percent – the latter respondent assigned a 10 percent chance of the virtual destruction of civilization! The 50th percentile damage estimate from this group was an order of magnitude higher than that of the economists. Nordhaus suggested that the ones who know the most about the economy were less concerned. I countered that the ones who know the most about the environment were more worried. The natural scientists, in essence, were less sanguine that human ingenuity could substitute for ecological services. Also, as Roughgarden and Schneider [80] showed, there was a positive correlation between the absolute amount of damage each respondent estimated and the percentage of total damages each assigned outside of standard national accounts (i.e., the natural scientists had higher percentages of their losses assigned to the non-market sectors). Regardless, either judgment involves both economic and ecological assessments, not single-disciplinary expertise. Clearly, the evolution of interdisciplinary communities cognizant of both economic and ecological knowledge and belief systems will be needed to make these subjective opinions more credible.

The differences in various respondents' estimates of climate damages were cast into subjective probability distributions by Roughgarden and Schneider [80] and then used to drive the Nordhaus [62] DICE model in order to recalculate its optimal carbon tax rate. The natural scientists' damage estimates processed by DICE produced optimal carbon taxes several times higher than either the original Nordhaus estimate or those of his surveyed economists. However, most respondents, economists and natural scientists alike, offered subjective probability distributions which were "right skewed". That is, most of the respondents considered the probability of severe climate damage ("nasty surprises") to be higher than the probability of "pleasant surprises". Because of this right skewness, even though the best guess of the economists for climate damages was comparable to original DICE, the optimal carbon tax DICE computes when the full distribution of economists is used is somewhat larger than either original DICE or the tax calculated using the economists' 50th percentile climate damage estimates. Clearly, the use of probabilistic information, even if subjective, provides a much more representative picture of the broad views of the experts as well as a fairer representation of potential policy insights from this IAM.

As for the paradigm gulf in concern expressed by the two distinct professional groups of experts, this stand-off in belief systems must be recognized by all users of IAMs, perhaps by explicitly incorporating menu options to allow users to experiment with alternative cultural values and preferences. One example is Van Asselt and Rotmans [100] who incorporate "cultural theory" into a reduced form of IAM. Which of the scientists, natural or social, Nordhaus interviewed are closer to the "truth" may one day be empirically determinable, but for the next decade or so, at least, the differences will remain paradigmatic. Regardless of this "truth", one policy-relevant certainty is that the optimal carbon tax calculated using damage estimates from the surveyed natural scientists is dramatically larger than the tax calculated using damage estimates from the surveyed social scientists (Roughgarden and Schneider [80]).

4.3. Orienting IAMs to deal with current policy debates

4.3.1. Timing of abatement: Slow now or later?

The ITC issue affects the time profile of costs of carbon abatement, itself a major component of the current international debate over carbon policies (e.g., Repetto and Austin [71]). The international policy community thus will turn to IAMs to help inform decision-makers on this complicated issue. Therefore, a few details on the "timing issue" here can both make the debate clearer and provide an example where IAMs can offer policy insights and/or spread confusion on the topic, depending on how well the user community understands the assumptions underlying "answers" stemming from different IAMs.

Richels and Edmonds [72] argued that the costs of a delayed abatement pathway would be much less than the costs of a more immediate abatement pathway, and this view was explicitly graphed in the IPCC [38] report by contrasting the costs of achieving the same CO_2 stabilization concentration targets with a constant emissions pathway and with Richels and Edmonds (RE) delayed stabilization pathway. Figure 9.30 of IPCC [38], contrasts these two hypothetical paths to a 500 ppm stabilization target in the 22nd century alongside of the business-as-usual (BAU) baseline emissions pathway (the latter being an ever increasingly upward emissions profile to 2100 AD). The hypothetical, immediate stabilization pathway RE chose for this illustration is stabilization of emissions at 1990 levels. The RE delayed abatement pathway for comparison postulates little departure in emissions from BAU until about 2015, and then a drop in the rate of growth of emissions until 2050, after which there is a decrease in CO_2 emissions to *below* 1990 AD levels. It is asserted that this is less costly than the steady, more immediate stabilization pathway, partly because new, lower-cost, low-carbon, more energy-efficient technologies will have been invented between now and 2050 thus allowing posterity to abate carbon much cheaper than could de done in the next few decades.

Considerable attention has been focused on the question of whether abatement of carbon dioxide emissions to reduce potential damages (e.g., IPCC [37]) from climate changes is more cost-effectively accomplished by delaying the bulk of the abatement activities by at least a few decades rather than implementing carbon dioxide reductions immediately. Wigley, Richels and Edmonds (hereafter referred to as WRE) [103] suggest that "pathways involving modest reductions below a BAU scenario in the early years followed by sharper reductions later on were found to be less expensive". They suggest four reasons why a pathway that leads to stabilization of carbon dioxide concentrations with delayed abatement activities is more "cost-effective" than a pathway that produces the same long-term (say by 2150 AD) concentration stabilization, but does more of the abatement immediately. First is the marginal positive return on capital – conventional discounting. Second, WRE say capital stock for energy production and end use can be long-lived and thus delayed abatement allows orderly replacement of expensive production assets with less carbon or energy intensive new technologies after the older stock has surpassed its economic lifetime. Third on the WRE list is technical progress, in which less carbon and energy intensive technologies are being invented and marketed increasingly over time, and thus the "availability of low-carbon substitutes will probably improve and their costs reduce over time". Fourth, carbon emitted sooner will be exposed longer to removal processes via oceanic and biospheric uptake pathways than carbon emitted in the distant future. Thus, WRE emphasize that, by delaying abatement until such improved technologies are more abundant and presumably less costly, the same long-term stabilization target can be achieved more cost effectively than by protocols which force more of the abatement to occur immediately.

4.3.2. Discounting dominates optimal control policy simulation results

However, WRE say at the outset that they do not consider the benefits (i.e., avoided climate damages) of policies that could reduce emissions. Such benefits could justify moving up the abatement profile. Moreover, since costs of abatement are likely to be felt sooner than benefits from avoided climate change from abatement policies, this displacement in time between costs and benefits obviously will make optimal control rates simulated in IAMs very sensitive to discount rates. Optimal policies employing differing discount rates, climate change estimates, and damage functions may, depending on assumptions, suggest very different policies with regard to the degree of delaying abatement (e.g., Roughgarden and Schneider [80]). We will not dwell here on the arguments in favor (e.g., Nordhaus [64]) of the conventional discounting assumptions nor those which suggest that in the case of non-market commons like climate impacts on nature (an issue not treated by WRE), where damages could be felt over an extended time horizon, that discounting the climate damage part of the assessment is not appropriate (Hasselmann et al. [31]). However, as such arguments are partly technical (e.g., see [38, chapter 4] or Heal [34]) and partly value judgments (e.g., Brown [5], Chichilnisky [7]), they are a very good illustration of why decision-makers need to be integrally involved in the design and use of IAMs' assumptions, such as discount rates.

4.3.3. Other critiques and responses to delayed abatement

The WRE suggestions for delayed abatement have been criticized on several additional grounds (e.g., Grubb [25], Ha-Duong [28], Azar [4], Hourcade and Robinson [35]). First, delayed abatement presupposes that future generations will have the political will – even if decisions to delay abatement do indeed leave future generations richer in conventional terms – to engage in vigorous abatement activities in order to meet rapidly approaching CO_2 concentrations targets, a burden that decades earlier their elders, for the reasons cited by WRE, chose to pass forward in time. Second, delayed abatement means more climate change earlier and at a faster rate, both of which could imply slightly higher climate damages (and perhaps a much larger chance of climate surprises – e.g., IPCC [36, p. 7]). Recognizing the potential risks of both large amounts and *rates* of climate change led to the "tolerable windows" approach to emissions (Alcamo and Kreilemen [3]). This idea suggests that emissions corridors wide enough to allow healthy economic growth, on the one hand, but narrow enough to prevent "dangerous anthropogenic climate change" – either more than an absolute amount of climate change (say, 2°C) in the long term or a large rate of climate change (say, 0.2°C per decade for several consecutive decades) in the shorter term – on the other hand, would comprise a "tolerable window" of emissions. Of course, what constitutes "healthy" growth or "dangerous" interference are the usual political value choices.

WRE reply to such criticisms by pointing out that they were not attempting to provide an optimal path in which the costs of abatement are somehow balanced against the costs of climate damage from non-abated emissions, and that they were only referring to the *cost-effectiveness of the timing* of abatement strategies which produce the same long-term CO_2 concentration stabilization. Indeed, it is quite possible that a more immediate, even if more costly, abatement protocol could be justified on economic efficiency grounds alone if such an optimization were performed. Indeed, maximizing economic efficiency, as typically calculated by economic optimization models (themselves subsets of comprehensive IAMs), is but one of a range of approaches to the IA of policy options. As noted earlier, the precautionary principle, risk aversion, stewardship or international and intergenerational equity are other policy principles (see, e.g., Van der Sluijs [101]). Although such principles could find expression within otherwise conventional cost/benefit calculations, we will not dwell further in this section on the integrated assessment of alternative policy principles, other than to repeat the need to provide "user friendly", probably menu-driven, ways to incorporate them into IAMs structure. With such options transparently available the models would not as easily become opaque screens hiding the value assumptions embedded in conventional economic efficiency optimization calculations.

WRE did not claim to have performed an IA, even though their work has been misrepresented by some in the public debate as favoring no immediate policy action. Rather, WRE respond to such criticisms, by noting that they state that "our results should not be interpreted as suggesting a 'do nothing' or 'wait-and-see' policy. To ensure sufficient quantities of low-cost, low-carbon substitutes in the future requires a sustained commitment to research, development and demonstration today" [103, p. 242]. They argue for the need to send signals to the energy sector to develop such technologies and to redress all current market failures on energy issues by actively pursuing so called "no regrets" options. The problem is that this caveat was too easily missed (or ignored) by some whose interpretation of the WRE model's "insights" did not even reflect the authors' own views. Perhaps this occurred because WRE, constrained by a limited number of journal pages, did not discuss *instruments* by which such a "sustained commitment" might take place.

In a subsequent commentary, Schneider and Goulder [92] (hereafter SG) elaborate on WRE's call for policies to immediately introduce actions that help to ensure sustained commitment to the very technological progress that WRE assume will permit the cost-effective strategy of delayed abatement. In particular, SG asked whether, on economic efficiency grounds alone, it is preferable to implement a sustained and immediate commitment to improved technical progress by direct subsidies to technological developers, or by a broader based incentive such as a carbon tax (or cap and trade policies).

Since technological progress is expected to allow lower-cost means of abatement in the future, this implies that, to reach a given target for emissions reductions, a world with more rapid technological change is likely to see lower abatement costs than a world of slower technological change. Three related issues arise: (a) in the presence of technological change, does it make sense to do any abatement now (and by what policy instruments?), (b) what present policies are required to bring about more rapid technological changes that will enhance future abatement?, and (c) what present policies might discourage locking into place in the near term high carbon emitting sources that will have lifetimes of many decades?

Integrated assessment models can help to provide insights on these questions that can help to inform the decision-making process *provided* (as I repeat here several times) the policy-makers understand the underlying assumptions within the IAMs and how they constrain the range of "answers" IAMs provide.

Goulder and Schneider [23] focus on R&D-based technological change. Goulder and Mathai [22], on the other hand, investigate the issue of opportunity costs applied to technological change resulting from "learning by doing". In the R&D-based assessment GS calculated that ITC could lower the optimal tax rate needed to achieve a particular level of abatement. Although this means ITC improves the cost-effectiveness of abatement, it also suggests that some abatement will be postponed relative to no-ITC models since a lower initial carbon tax will mean less initial abatement than a higher tax. (On the other hand, the higher the level of a carbon tax imposed – or at least announced – now, the more this policy instrument will discourage locking high carbon emitting energy systems into place that will have many decades of economic life-time in developed or developing countries.)

Learning-by-doing, on the other hand, can also weaken the case for delaying abatement since technological progress which is induced by carbon abatement policies in the near term can lead to early and rapid knowledge accumulation. Thus delay in abatement in this context is "learning opportunity lost". However, as noted above, learning by doing also leads to ITC, which in turn, lowers initial carbon tax rates, which, like the R&D based assessment of GS, pushes optimal abatement back in time on cost-effectiveness grounds. In summary, Goulder and Mathai argue that ITC has different potential implications for the cost-effectiveness of timing of abatement depending upon whether the technological progress is induced by enhanced R&D investments or by learning by doing. And, all of this depends on the six caveats given in the ITC section earlier.

4.3.4. Using IAMs to assess alternative abatement instruments

Another question that IAMs can also address is whether it is more economically efficient to invest in abatement incentives via direct R&D subsidies or via a broader based policy instrument like a carbon tax. That issue, which was briefly introduced above, is discussed in detail in SG. In short, SG conclude that if there are no prior distortions in R&D markets that a carbon tax is many times more efficient than technological subsidies to achieve a certain abatement target. However, since R&D markets are rarely efficient, some combination of carbon taxes, R&D subsidies and/or cap and trade policies would be the most economically efficient pathway towards some CO_2 stabilization target (again, assuming that optimizing efficiency is the politically preferable paradigm – e.g., see Van Asselt and Rotmans [100]). Some have objected to carbon taxes, regardless of efficiency, as being regressive. Others have responded that revenue recycling could accompany a carbon tax and be used to either further improve efficiency by offsetting a less efficient tax and/or by offsetting a more regressive tax (see the debate on the so-called "double dividend": Jorgenson et al. [41], Goulder [20,21], Hamond et al. [29]).

This discussion once again provides an example of the use of models for insights that can inform the policy-making debate *provided* decision-makers are aware of the many assumptions embedded in the modeling exercises (e.g., R&D resources are scarce and shifts in R&D priorities have opportunity costs, or rapid rates of climate change might increase the chances of surprises). Decision-makers also need to be aware of the limited context of many IAMs: economic efficiency optimization based on "best guess" climate damages for a U.S.-like market economy rather than non-market based economies, equity considerations or hedging strategies against low probability, catastrophic outcomes.

5. Concluding remarks

Integrated assessment models are the primary analytical tools now available to study the connected physical, biological, and social components of global change problems created by hypothetical global change disturbances. Case studies (e.g., Crosson and Rosenberg [10] or Glantz [19]) can help to identify concepts or processes that should be incorporated in the IAMs, but are less useful for sensitivity analyses than analytic methods. While indispensable for asking logical "what if" questions, such as the cost-effectiveness of alternative policies or the economic efficiency of carbon taxes versus R&D subsidies, IAMs can only produce "answers" that are as good as their underlying assumptions and structural fidelity to a very complex multi-component system.

Returning to the question posed in the sub-title of the article, how can IAMs be constructed and used so as to increase transparency and reduce the likelihood of either misrepresentation or misunderstanding? I will not claim to offer a comprehensive set of criteria (see also table 4 and Ravetz [70]), but do provide the following as a partial checklist of issues or practices to bear in mind when building or applying IAMs to the IA of climate change issues:

1. Specify clearly at the outset and in the conclusions of presentations or publications the limited context of each particular IAM exercise.

2. Cite alternative approaches and contrast them to your approach, stressing how each treats uncertainty and deals with the many value-laden components of the analysis.

3. Provide as many menu options as practical, especially for those choices which deal with culturally-dependent components or "imaginable surprises".

4. Perform as many "validation" tests as possible, and when not practical, discuss, based on qualitative reasoning, the credibility of structural assumptions, input data, and model parameters, and their relevance to policy issues are being considered.

5. Stress the likelihood that this generation of IAM results will change as "rolling reassessments" provide an evolving picture of climatic effects, impacts and the efficacy of policy instruments and societal values.

6. Note components of the IAM which are particularly sensitive (or insensitive) to aspects of the problem that are controversial and thus likely to change with evolving research.

I believe that the integrated assessment process is most valuable as it develops into an expanding community of scholars, analysts, technologists, decision-makers and citizens, each increasingly informed about the strengths and weaknesses of each other's work and the potential responses of the interacting physical, biological and social systems of the Earth – embodied in a hierarchy of IAMs – to human disturbances at local, regional and global levels. The daunting complexity of this problem precludes confidence in the answers from any one approach, but holds the promise of providing growing insights as new approaches are offered, the results are compared to existing efforts, all models are evaluated against available each other and empirical data, and their underlying assumptions are made transparent and accessible to alteration by a user community that has participated in both the design and application of each category of IAMs. It would be as foolish not to take the hedged qualitative insights from a family of IAMs seriously as it would be to take their individual quantitative results literally.

The cultural differences across professional or other social groups must also be explicitly accounted for in IAMs. For example, it is not good stewardship or economics to mortgage our environmental future and leave the burden of finding solutions to our posterity, ecologists typically argue. But we are leaving them more wealth to cope with these burdens, economists typically retort, which will allow posterity more flexibility to deal more cost-effectively with ecological disturbance. In other words, which is "better": a legacy of highly developed infrastructure and wealth or a legacy of environmental disturbance and biotic impoverishment? Finding the balance of values across this cultural dichotomy is what the political system is supposed to do – but first it must recognize the assumptions and belief systems embedded into any of the analytical tools that are designed to inform the process. Indeed, such tools, like IAMs, can help to describe quantitatively the logical consequences of an explicit set of assumptions – including those of differential values and beliefs. Beyond that, values and beliefs take over. Our responsibility as IAM builders and users is to make such values and beliefs transparent and accessible in our products.

But even apparent transparency may hide values: "Computer displays which attempt to be transparent may unintentionally produce a false sense of simplicity and clarity", Ravetz [70] worries. He suggests it "will be a task involving all the talents, to establish a dialogue across the barriers, intellectual and social, of exclusive expertise. In the ULYSSES (a European research project that aims to bridge the gap between environmental science and democratic policy making in the climate domain), we are just now beginning the series of experiments in such communication among citizens, preparing to make those necessary mistakes from which we intend to learn." It will be very interesting to watch the ULYSSES experiment to see how focus groups that include "ordinary citizens" interact with climate intellectuals in a way that both will complement and improve IAMs in the IA process.

Most critical, then, is the need for IA modelers to engage in a vigorous outreach program to entrain decision-makers and citizens at all levels into the process of helping to design, test and use IAMs for real policy questions. This demands transparency and accessibility, and that all values and assumptions that might be hidden in the analytic complexity of IAMs are purposefully made explicit to users – hopefully as options within a framework of "user-friendly", menu-driven software. To do less is to make IAMs at best irrelevant to policy-makers, and at worst, misleading. It is a challenging task, but worth the attempt, since I believe it is likely that IAMs can explore the behavior of complex systems more reliably – and certainly more consistently – than mental models, *provided* the embedded assumptions in the IAMs are clearly seen and understood by the users. Then, citizens re-enter to make the value judgments that are their franchise, hopefully more aware – thanks to insights from IAMs – of the estimated ranges of outcomes and distributions of costs that each proposed policy entails.

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