GLOBAL COMPREHENSIVE MODELS IN POLITICS AND POLICYMAKING

Editorial Essay

PAUL N. EDWARDS
Program in Science, Technology & Society Bldg. 370, Rm. 111, Stanford University Stanford, CA 94305-2120, U.S.A.

In this issue of *Climatic Change,* Ron Brunner argues that the US Global Change Research Program (USGCRP) has – to its peril – overemphasized the potential policy significance of comprehensive, predictive models [1]. Brunner thinks that although comprehensive models are properly a central goal of global change *science*, they cannot produce effective global change *policy*. He argues for a 'modest alternative' to comprehensive modeling and policymaking. The alternative consists of geographically decentralized 'policy teams' which would generate and test a wide variety of limited policy formulations and action alternatives on a regional or even local scale over a short (2-3 year) cycle.

The problem, in Brunner's view, is fourfold. First, predictive global models do not now have, and are unlikely soon to reach, very high levels of accuracy. While model quality is being debated and improved, public confidence in the USGCRP is eroding. Furthermore, authoritative validation of integrated assessment models (IAMs) is at least unlikely, if not altogether impossible, because they include socio-economic processes subject to large future modifications by intelligent social decision-making and by unpredictable human events. Second, predictions – even excellent ones – are not very important to the ways policies are actually established and evaluated in America (and perhaps, though he does not say so, in democratic societies in general). Thus even if highly accurate, thoroughly validated models existed, they would not matter much to the policy process. Third, if and when they materialize, actual global change policies are themselves unlikely to be comprehensive, simply because consensus on *any* comprehensive policy is very difficult to achieve. Finally, because it focuses primarily on national and international-level policy and because its rigorous demands limit the number of models it can produce, the comprehensive approach risks overlooking effective policy options at smaller scales. For these reasons, Brunner believes, policymakers would be better served by efforts to proliferate, experiment with, and evaluate a wide variety of limited, non-comprehensive policy alternatives.

In this editorial, I reflect on the role of comprehensive models, such as IAMs and earth system models (ESMs), in politics and policymaking [2]. I distinguish between the latter terms because part of what I will address is the importance

Climatic Change **32:** 149–161, 1996.

of comprehensive model-building in generating an 'epistemic community' [3, 4] which includes not only scientists, but policymakers and other agents and institutions with compelling interests in global change issues. I will argue that the emergence of such a community is one major reason why global change has reached the political agenda of governments, and thus that comprehensive model-building serves an all-important political purpose even if it does not and perhaps cannot serve the immediate needs of policymakers.

My second point will be a recent historical analogy. The 'limits to growth' debate of the early 1970s – similar to contemporary global change debates in the limited sense that comprehensive computer models of socio-technical-environmental systems underlay its major claims – demonstrates another way models can acquire political significance, namely as purely heuristic guides to complex phenomena. The analogy also demonstrates some of the pitfalls of this use of models, especially when they are downscaled to the regional or local level.

Finally, I will consider the issue of whether regional or local policies can provide a real alternative to comprehensive national and international policy in the global change area. Here I will argue that while regional/local efforts have merit and should be attempted, the same problems of policy incentives that inhibit comprehensive international policymaking apply to them as well. Since isolated regional or local policies would have no noticeable effect on global change *per se*, they would have to offer other, more concrete benefits as well. One such benefit might be a salutary effect, via example-setting and concept-proving, on the production of policy at larger levels.

1. Comprehensive Models and Scientific Politics

Global change scientists – including social scientists – are approaching the problem of comprehensive models from two directions. The first, 'earth system' or 'earth systems' models (ESMs), is a direct extension of natural-science efforts to couple oceanic and atmospheric general circulation models (OAGCMs) in climate simulations. The goal is to couple models of other climate-related systems (land surface, sea ice, etc.) to an OAGCM, eventually capturing all of the major elements of the total climate system – including anthropogenic effects such as agriculture and artificial greenhouse gas release [5, 6, 7, 8, 9]. In general, sophisticated models of human socio-economic activities have been last in line for integration into ESMs, which focus most of their effort on natural systems [10, 11, 12, 13]. Most of these models descend from existing GCM efforts.

The second type of effort, 'integrated assessment models' (IAMs), has a different origin, namely the goal of understanding human impacts on climate and the costs and benefits of possible mitigations [14, 15, 16, 17, 18]. IAMs typically do not incorporate GCMs directly. Instead, they rely either on selected and aggregated GCM outputs or on much simpler energy-balance climate models [19]. Their purpose is to allow rough, rapid analysis of the possible effects of various politico-economic scenarios on climate change. In contrast to earth system modelers, IAM developers generally spend much more of their energy on the social, political, and economic elements of their models, relying for the natural-systems side on outputs from other efforts based in the natural sciences. Some IAMs are descended from energy and emissions models originally built for 1970s-era economic and environmental forecasting; others owe a direct debt to the system dynamics models of Jay Forrester and his followers.

Earth-system modelers' primary interest is in fully comprehensive, highly accurate, highly detailed natural-systems models that are potentially *predictive* in the traditional scientific sense, i.e., ideally they would extrapolate future trends by applying natural laws to raw data. By contrast, IAM developers are typically engaged in rough, order-of-magnitude modeling which attempts to be comprehensive only in those areas most directly related to human activity, such as energy and agriculture. IAMs incorporate empirically derived trends, heuristics, and unproven or qualitative theories into their modeling techniques far more freely than do ESMs. Their goal is (or ought to be) *comparison* of policy scenarios and *forecasting* of trends, not *prediction* at statistically significant levels; this is the point of the term 'assessment.' Not all IAM outputs are global in scope; for example, the first IMAGE model focused primarily on the Netherlands [17, 20]. Many IAM builders hope that their models – unlike the hyper-complex, supercomputer-based ESMs – will be simple, transparent, and portable enough that policymakers, or perhaps their staffers or administrative agencies, can engage with the models directly. If so, they could observe for themselves, on a desktop computer, the differential effects of various politico-economic scenarios, such as carbon taxes, population stabilization, or reforestation efforts, on global change. The idea is to offer policymakers an effective way to learn a set of *heuristics* – a quasi-intuitive 'feel' or rule of thumb based upon, yet not fully determined by, data-driven analysis – for global change policy options. IAMs, then, are inherently policy-oriented, while ESMs are not.

Both kinds of models have become the focal points of a relatively new, very broad effort to integrate results and methods from many different sciences. Social, behavioral, economic, and policy sciences are part of this mix, albeit more so in IAMs than in ESMs. Doing this kind of modeling means that each discipline must ultimately embody its data and principles in computer code that can 'talk' to the model's other modules (i.e. perform 'intermodel handoffs').

A much more important cross-talk among scientists from different disciplines occurs during this process [22]. ESMs, in addition to encouraging trans-disciplinary collaboration, build an important epistemological bridge to the problematic observational record on global change. None of the available observational data sets remotely approach what might be construed as a minimal requirement for truly 'global' climatological data, i.e. coverage of the entire Earth on (say) an 0.5° latitude by 0.5° longitude grid at twenty or more altitudes, using consistent measuring techniques and well-calibrated instruments, with at least twice-daily sampling over a period of at least one hundred years. Instead coverage is spotty, inconsistent, badly gridded, poorly calibrated, and/or temporally brief [7, 23]. Rather, it is the *models* which are 'global'; the data, with the exception of the (not unproblematic) satellite measurements, are local, or regional at best. Part of the work of the models is to make those data function *as* 'global' by providing an overarching reference frame [24, 25]. Thus IAMs and ESMs are increasingly the foci of an emerging 'epistemic community.'

This is Peter Haas's term for a knowledge-based professional group which shares a set of beliefs about cause-and-effect relationships and a set of practices for testing and confirming them. Crucially, an epistemic community also shares a set of values and an interpretive framework; these guide the group in drawing policy conclusions from their knowledge. Its ability to stake an authoritative claim to knowledge is what gives an epistemic community its power [3, 4]. In the arena of global change science, where wholly empirical methods are infeasible, computer modeling has become *the* central practice for evaluating truth claims. The wide-ranging ramifications of models as an experimental domain are best discussed elsewhere [26, 27, 28, 29]; one of them, however, is clearly that models are now a – perhaps *the* – key medium for translation and migration of data, methods, and guiding principles among the disciplines involved. They lie at the center of the epistemic community of global change science. In the case of ESMs and IAMs, this includes climate and paleoclimate science, oceanography, ecology, energy modeling, economics, agronomy, and a variety of other sciences.

Thus whether or not they are ever used directly by policymakers, these models are contributing to what I believe to be a fundamental shift in the structure of scientific work toward trans-disciplinary collaboration and communication. This means that ESMs and IAMs in fact contribute substantially to the basis of global change *politics*, in the important sense that they serve as one of the organizing principles of a large, growing, epistemologically coherent community. This community shares the crucial belief that *global* natural systems may be significantly affected by human activities – a belief to which very few would have subscribed three decades ago. I would argue that it also, in general, shares the values that such systems are worth preserving and that rational political decisionmaking can be achieved, at least to some degree, which could preserve them. Integrated model-building contributes directly to this base of common assumptions, to a scientific macro-paradigm that accepts computer simulation as a substitute for (infeasible) traditional forms of experimentation, and to a network of individuals, laboratories, and institutions such as the USGCRP and the Intergovernmental Panel on Climate Change (IPCC). The models help to create a public space, including shared knowledge, shared values, and access to common tools and data, for consensus-building on global change issues.

So global models' lack of predictive accuracy on specific forecast scenarios does not mean that they serve no scientific or political purpose. Instead, models – as transportable artifacts which embody and communicate community assumptions, beliefs, and shared data – already serve such a purpose vis-à-vis the internal politics of the scientific community and its relations with non-scientific actors, including policymakers. In this very important, entirely non-pejorative sense, comprehensive model-building is simultaneously scientific and political [26, 30, 31].

I will leave the question of whether ESMs or IAMs can contribute to effective global change *policymaking* for the final section.

2. A Recent Historical Analogy

I am constantly surprised by the degree to which the first simulations that could truly be called integrated assessment models – the 'world dynamics' models of Jay Forrester – have been forgotten by the global change community. Forrester, earlier one of the most important pioneers of digital computing, invented 'system dynamics' (numerical modeling of complex systems featuring multiple feedbacks) at MIT in the late 1950s [32, 33]. He applied this technique first to factories, then to cities, and finally, in the late 1960s, to the world as whole [34, 35, 36, 37].

Supported by the Club of Rome – an international group of about 100 prominent businessmen, scientists, and politicians organized by Italian industrialist Aurelio Peccei – Forrester developed three successive world models. The models divided world systems into five major subsystems: natural resources (primarily non-renewables), population, pollution, capital, and agriculture. The most sophisticated model, 'World 3,' incorporated over 120 strongly interdependent variables [37, 38]. World dynamics' essential premise was that many existing trends (resource consumption, pollution increases, population growth, etc.) displayed exponential growth rates which a finite planet could not possibly sustain [39]. Model runs based on existing trends predicted that natural resources would be rapidly exhausted, that 'pollution' – in the models, a single quantity – would rapidly increase to life-threatening levels, and that catastrophic collapse, including massive famine, would follow around the year 2050. Holding one or a few key variables constant (e.g. population or natural resources) generally delayed but, because of interacting feedbacks with other variables, did not evade catastrophic collapse. Only a systematic approach that stabilized *all* the important trends produced a sustainable future. The two major conclusions were (a) that population, pollution, and consumption levels could not continue to grow indefinitely, and (b) that attempts to control problems piecemeal, without taking into account the interconnected nature of world socio-technical-environmental systems, would not work and might actually backfire. All of this will seem extremely familiar to readers of *Climatic Change*.

The data used to initialize the world models were generally poor in quality. In many cases, they were simply guessed. Similarly, the choice of both variables and feedbacks was mostly an intuitive exercise not based on empirical research. As for quantifications of feedback relationships, these too were essentially made up by Forrester's group. Naturally, then, the models drew heavy fire from the scientific community (including especially economists) upon their release, and within a couple of years most scientists regarded them with indifference or even contempt [40, 41]. Many in the policy community found the world-models approach – in an era when computer simulation was far less widely understood and accepted than today – technocratic in the extreme. This impression was only amplified by the Club of Rome's élite character and by the perceived arrogance and insensitivity of some of the modelers [42].

Yet *The Limits to Growth* (a popularized version of the technical report *World Dynamics)* became an international phenomenon, selling over three million copies worldwide in some thirty languages [39]. During the rest of the 1970s, the Club of Rome commanded considerable international respect. It convened a series of meetings among senior politicians to discuss the world 'problématique,' as they called it. Meetings held in major world capitols occasionally included the presidents and prime ministers of such nations as Canada, Sweden, the Netherlands, and Mexico [43]. A series of follow-ups to the original world models were built [44, 45, 46]. One important follow-on from this work was the establishment of the International Institute for Applied Systems Analysis (IIASA) in Vienna, a research organization now frequented by many of today's generation of global modelers.

It is doubtful that either *The Limits to Growth* or the Club of Rome had any *direct* policy impacts at all. Nevertheless it is certainly true that through its models, popular books, meetings, and person-to-person canvassing of politicians, the Club succeeded in communicating – to both a broad public and a policy élite – its two basic heuristics: (a) that exponential growth (especially in population) cannot continue unchecked, and (b) that the world should be viewed as a set of interlocking systems which cannot be successfully understood or managed piecemeal. It is safe to say that these principles fairly rapidly achieved the status of shared background assumptions for at least a large subset of the world policy community. The world dynamics modelers also successfully established computer simulation as an important technique of policy analysis. In the process they – like today's global change modelers – built a hybrid science/policy community for which the models were a key focal point.

The *Limits to Growth* modelers – like today's IAM builders – never claimed great accuracy for their predictions, but rather intended merely to demonstrate a few key qualitative principles. It was the very simplicity of this goal which gave their work so much rhetorical force. Yet a major critique of the original world dynamics models was that they produced only global aggregate results. World economic and resource networks were not sufficiently integrated, many argued, for this to make sense. Disaggregating the models into regions might produce quite different results. Indeed, the second Club of Rome report did just that [40, 45, 47]. But neither this nor the series of regionally disaggregated models that followed had anything like the impact of the original world models.

Here lies another important parallel to the contemporary situation. In political debate, uncertainties in comprehensive global models become a resource which can and will be employed by different interests in different ways [27]. For opponents of immediate action, uncertainties in both global and regional model-based projections obviously provide a time-worn rationale for shunting funds and attention back to 'basic' research, or for denying the validity of climate change projections [48, 49, 50, 51]. But proponents of near-term action can also use these uncertainties strategically, in at least two ways. First, like the world dynamics modelers, they can argue that the models should not be interpreted (politically) as exact predictions, but rather as heuristics about the likely direction and nature of global change [7, 52, 53]. Since policymakers – as Brunner himself argues – tend to base their decisions on heuristics rather than forecasts anyway, this interpretation is in my view more likely to lead to action than insisting on exact predictions which can then be challenged in their details. In this limited sense, the models have *already* had quite substantial political impacts [54]. Second, as long as large regional uncertainties remain, models whose results are seen as valid only for global averages can fuel a one-world, globalist approach to global change politics. By preventing the identification of clear winners and losers in advance, the very lack of accurate regional climatic forecasts helps render global change issues more unifying than divisive. Far from inhibiting decisions, then, uncertainty can actually provide proponents of international- and national-level policymaking with one of their best arguments for near-term action.

3. Regional or Local Policies on Global Change?

But can ESMs or IAMs contribute *directly* to effective global change policy, defined as specific, short-term, practical efforts to affect the course of global change? Here I think the issue is rather more cloudy. The problem was neatly captured for me by NCAR ocean modeler Bob Chervin, who joked that GCMs will achieve direct policy impact 'only when their grid scales descend to the size of a Congressional district.' Democratic policy processes generally depend upon an ongoing series of short-term course corrections based on feedbacks from a variety of sources, including empirical observation, changing forecasts, and (by far the most important) the pressures of constituent groups. The latter, in turn, are influenced by each group's own beliefs about whether a given policy is effective and/or palatable.

Therefore, as Brunner also observes, the incentives which influence policymakers most in technical decision-making tend to reward projects that

a) are narrowly focused,
b) have a high probability of success,
c) can produce a steady series of short-term payoffs or milestones, and
d) have tangible, easily perceived, widely desired benefits [55].

These are merely the facts of life in the policy world, where many actors' motives are governed by the demands of the election cycle. It should be obvious from the events of the last two years that in the current Congress, at least, concerns like these

– together with a fifth element, perceived financial affordability – now dominate most national political decisions [56].

As a thought experiment, imagine that the best conceivable international, *comprehensive* global change policy (regulating, say, not only greenhouse gas emissions and energy efficiency, but agriculture, forestry, population, and economic development) were somehow instituted tomorrow: none of these conditions would apply. Such a policy would be the most complex, wide-ranging international agreement ever attempted. No existing institution would have enough power to enforce it. Because of delays inherent in the climate system, this policy would probably merely mitigate global warming (rather than eliminate it); it might not even succeed in this limited aim, because of the possibility of unpredictable climate-altering natural events (e.g. major volcanic eruptions). Some of its near-term costs would certainly be substantial [57]. Its benefits to global climate would take a very long time (probably decades) to materialize, and would in any case be diffuse and difficult to perceive. Since the climate is highly variable anyway, few milestones would mark the path of progress. Finally, in fact, *perception of these benefits would itself depend on models*, since there would be no other way to know what would have happened without the policy. (This last point is an important one, since it indicates one potential role for models that has rarely been highlighted.) Thus from the point of view of traditional political reasoning, achieving a comprehensive international policy on global change would seem highly unlikely in the near term.

Yet this way of understanding the policy process can be deceptive if interpreted to mean that large-scale, comprehensive policies are doomed from the start. The characteristics mentioned above are in fact neutral with regard to the scale or the comprehensiveness of the policy – if it can be *formulated as* narrowly focused. The NASA moonshots were an excellent example of just such a successful expensive, large-scale project: an apparently narrowly-focused, goal-oriented program which served in fact simultaneously as a major socio-economic policy (regional development in the Southern US) and a Cold War politico-military policy (the space race; establishment of rights of overflight for spy satellites) [58].

Furthermore, the evidence of the last decade suggests that quite robust, if not entirely comprehensive, policy could conceivably emerge fairly quickly. The current domestic political situation is a tide that can be turned by the right combination of events and efforts. A near-comprehensive international policy on ozone depletion was established in just five years (from the 1985 Vienna Convention to the 1990 London Amendments phasing out chlorofluorocarbons). Although the climate change issue is clearly far more complex, national policies on climate change (albeit relatively weak and not yet truly comprehensive ones) have already been instituted in some countries. The Framework Convention on Climate Change was signed in 1992 – yet climate change emerged as an international political issue only in the summer of 1988 [54, 59]. In my view, this happened primarily because of at least five independent factors: (a) the US summer drought of 1988, with its attendant media attention, (b) the rapid decline of Cold War politics, which left behind it a sort of 'apocalypse vacuum' readily filled by global warming scenarios, (c) the 'nuclear winter' debates of the early 1980s, which first elevated the issue of anthropogenic climate change to the level of front-page news, (d) the 'ozone hole' issue of the mid-1980s, another piece of front-page news concerning anthropogenic atmospheric change, and (e) a rising crescendo of scientific and environmental activism at the international level, the political elements of which saw the potential of global warming and ozone depletion as world-unifying environmental concerns. I mention this because computer models played substantial – even decisive – roles in (c), (d), and (e) at the level of scientific consensus-building.

Thus to the extent that comprehensive modeling helps to build an epistemic community to develop and spread heuristics about global change, and to inform policymakers about the general extent and structure of the problem, I think it can only be a net benefit. I do not share Brunner's belief that models are largely *irrelevant* to policy; instead, I think that the *way* in which they are relevant to policy must be more subtly understood. The coupling of models to policy is (and should be) weak and heuristic rather than strong and deterministic, and it is mediated by the formation of epistemic communities.

Returning to Ron Brunner's other questions, would an expanded policy research program help establish effective global change policies more quickly? I think the answer to this question is probably yes. Brunner is entirely right that the reason policymakers have not taken action has little to do with a desire for better predictions. It has much more to do with their perception that strong global change policies would threaten entrenched interests and reduce economic growth. Policymakers would certainly benefit from a large and expanding menu of creative ideas for policies with the characteristics mentioned above, ones which could offer focused, near-term goals and wide-ranging, tangible benefits while minimizing adverse impacts on affected groups.

Would an alternative to global, comprehensive approaches – a regional or local alternative, like Brunner's 'policy teams' – stand a better chance of near-term success? Maybe, but I think this is less likely. It would be stupid to dismiss such a possibility out of hand, since it is surely an empirical question whether small policy research projects could succeed more quickly than large ones in producing attractive options or in putting them into effect. Indeed, were I in a position to do so, I would probably fund a few of them to find out. However, global change issues have special features that make them quite different from the energy-crisis-response policies that constitute Brunner's examples of successes. The feedback problems with comprehensive policies discussed above apply in spades to local or regional (sub-national) policymaking. Suppose that a city like Boston or a state like California managed to implement a policy, such as a carbon tax or a reforestation program, aimed at the goal of reducing global warming. How would constituents learn whether their policy had helped solve the problem? What short-term, tangible benefits would accrue? Since such an effort would have no *measurable* near-term effect on global warming at all, the only way to determine the policy's value would be by modeling the effects of implementing it on a larger scale. Therefore, to succeed in most communities, such policies would have to offer other, more concrete benefits beyond any putative effects on global change.

The local/regional policy approach would offer one key benefit which Brunner does not mention. Studies of international environmental policy have shown that the single most important variable accounting for policy change is domestic pressure from environmental constituencies [60]. Effective local/regional policies, if widely popular, might help build momentum in this direction. If that were all they accomplished, they would still be worth the effort. If they marked new directions that could be duplicated on a larger scale, they would be a resounding success.

Notes and References

1. Brunner, R.: 1996, 'Policy and Global Change Research: A Modest Proposal,' *Climatic Change*.
2. My views are based on three kinds of data: (1) interviews I have conducted over the past 18 months of some 40 American climate scientists, primarily but not exclusively modelers, (2) a survey of literatures on computer modeling in a variety of areas, especially artificial intelligence, system dynamics, and climate modeling, and (3) literatures in sociology, history, and policy studies of science and technology. Most of my work to date has concerned the history, politics, and culture of computers and computer models in artificial intelligence and cognitive psychology. See, e.g., P.N. Edwards: 1987, 'A History of Computers in Weapons Systems,' *Computers in Battle,* D. Bellin and G. Chapman, Eds., Harcourt, New York, pp. 45-60; P. Edwards: 1994, 'From "Impact" to Social Process: Computers in Society and Culture,' *Handbook of Science and Technology Studies,* S. Jasanoff, T. Pinch, G. Markle, and J. Petersen, Eds., Sage Publications, Beverly Hills, CA.; P.N. Edwards: forthcoming, *The Closed World: Computers and the Politics of Discourse in Cold War America,* MIT Press, Cambridge, MA. Since early 1994 I have been working on a long-term project on the history and politics of the global climate change issue. See S. Jasanoff, B. Wynne, F. Buttel, A. Elzinga, P. Haas, M. Lynch, F. Charvolin, P. Edwards, C. Kwa, W.H. Lambright, and C. Miller: forthcoming, 'Scientific Knowledge and Decisionmaking,' *State of the Art Report on Climate Change,* Battelle–Pacific Northwest Laboratories.
3. Haas, P.: 1990, *Saving the Mediterranean: The Politics of International Environmental Cooperation,* Columbia University Press, New York.
4. Haas, P.M.: 1990, 'Obtaining International Environmental Protection through Epistemic Consensus,' *Millennium* **19**, 347-364.
5. Meehl, G.A.: 1992, 'Global coupled models: atmosphere, ocean, sea ice,' *Climate System Modeling,* K.E. Trenberth, Ed., Cambridge University Press, Cambridge, pp. 555-581.
6. S.H. Schneider: 1992, 'Introduction to Climate Modeling,' *Climate System Modeling,* K.E. Trenberth, Ed., Cambridge University Press, Cambridge, pp. 3-26.
7. Schneider, S.H.: 1994, 'Detecting Climatic Change Signals: Are There Any "Fingerprints"?,' *Science* **263**, 341-347.
8. Trenberth, K.E., Ed.: 1992, *Climate System Modeling,* Cambridge University Press, Cambridge.
9. Turner II, B.L., Moss, R.H., and Skole, D.L.: 1993, 'Relating Land Use and Global Land-Cover Change,' *IGBP Report 24,* International Geosphere-Biosphere Program.
10. Thompson, S.L. and Pollard, D.: 1995, 'A Global Climate Model (GENESIS) with a Land-surface-transfer Scheme (LSX). Part 1: Present-day climate,' *Journal of Climate* **8**, 732-761.
11. Thompson, S.L. and Pollard, D.: 1995, 'A Global Climate Model (GENESIS) with a Land-surface-transfer Scheme (LSX). Part 2: CO2 Sensitivity,' *Journal of Climate* **8**, 1104-1121.
12. Pollard, D. and Thompson, S.L.: 1994, 'Sea-ice Dynamics and CO2 Sensitivity in a Global Climate Model,' *Atmosphere-Ocean* **32**, 449-467.

13. Pollard, D. and Thompson, S.L.: 1995, 'Use of a Land-surface-transfer Scheme (LSX) in a Global Climate Model (GENESIS): The Response to Doubling Stomatal Resistance,' *Global and Planetary Change (MECCA Special Issue)* **10**, 129-161.
14. Dowlatabadi, H. and Morgan, M.G.: 1993, 'A Model Framework for Integrated Studies of the Climate Problem,' *Energy Policy* **21**, 209-221.
15. Alcamo, J.: 1994, *IMAGE 2.0: Integrated Modeling of Global Climate Change*, Kluwer Academic Publishers, Boston.
16. Hope, C.: 1993, 'Policy Analysis of the Greenhouse Effect: An Application of the PAGE Model,' *Energy Policy* **21**, 327-338.
17. Rotmans, J.: 1990, *IMAGE: An Integrated Model to Assess the Greenhouse Effect*, Kluwer Academic Publishers, Boston.
18. Rotmans, J.: 1992, 'ESCAPE: an integrated climate model for the EC,' *Change* **II**, 1-4.
19. 'USGCRP support for integrated assessment methods will enhance efforts to develop reduced-form models that mimic the more complete natural science process models.' National Science and Technology Council Committee on Environment and Natural Resources Research: 1995, *Our Changing Planet: The FY 1995 U. S. Global Change Research Program*, Global Change Research Information Offices, Washington, D.C., 26. Radical policy shifts now taking place under the 1995 Republican Congress may, however, have substantial impacts on this stated goal.
20. A more recent version, IMAGE 2.0, provides scenario analysis for 13 world regions defined primarily by economic characteristics (15).
21. Root, T.L. and Schneider, S.H.: 1995, 'Ecology and Climate: Research Strategies and Implications,' *Science* **269**, 331-341.
22. The transformative effects of model-building have been strongest, perhaps, on ecology. In order to match the global and temporal scales of climate models, ecologists have had to work hard to extrapolate from their traditional $100m^2$plots and annual time scales (21).
23. Houghton, J.T., Filho, L.G.M., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N., and Maskell, K., Eds.: 1995, *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*, Cambridge University Press, Cambridge.
24. Taylor, P. and Buttel, F.: 1992, 'How Do We Know We Have Global Environmental Problems?,' *Geoforum* **23**, 405-416.
25. Kiehl, J.T.: 1992, 'Atmospheric general circulation modeling,' *Climate System Modeling*, K.E. Trenberth, Ed., Cambridge University Press, Cambridge pp. 319-369.
26. Shackley, S. and Wynne, B.: 1995, 'Global Climate Change: The Mutual Construction of an Emergent Science-Policy Domain,' *Science and Public Policy* **22**, 218–230.
27. Shackley, S. and Wynne, B.: 1996, 'Representing Uncertainty in Global Climate Change Science and Policy: Boundary-Ordering Devices and Authority,' *Science, Technology and Human Values*, forthcoming.
28. Maisel, M.: work in progress, Ph.D. thesis, Science Studies Program, University of California, San Diego.
29. Edwards, P.N.: 1995, *Computer models and the politics of atmospheric science*, in A. Engels and P. Weingart, Eds., Climate Communications as a Research Field for the Social Sciences, Center for Interdisciplinary Research, Bielefeld, Germany, .
30. Jasanoff, S.: 1990, *The Fifth Branch: Science Advisors as Policymakers*, Harvard University Press, Cambridge, Mass.
31. Jasanoff, S.: 1991, 'Science, Politics, and the Renegotiation of Expertise at EPA,' *Osiris* **7**, 195-217.
32. Redmond, K.C. and Smith, T.M.: 1980, *Project Whirlwind: The History of a Pioneer Computer*, Digital Press, Boston.
33. Edwards, P.N.: forthcoming, *The Closed World: Computers and the Politics of Discourse in Cold War America*, MIT Press, Cambridge, MA.
34. Forrester, J.: 1969, *Urban Dynamics*, MIT Press, Cambridge, MA.
35. Forrester, J.: 1961, *Industrial Dynamics*, MIT Press, Cambridge, MA.
36. Forrester, J.: 1968, *Principles of Systems*, Wright-Allen Press, Cambridge, MA.
37. Forrester, J.: 1971, *World Dynamics*, MIT Press, Cambridge, MA.

38. Interestingly, though it did not appear as a variable, a graph of atmospheric carbon dioxide measurements from Mauna Loa was displayed in *The Limits to Growth* as an example of exponential growth in pollution.
39. Meadows, D.H., Meadows, D.L., Randers, J., and Behrens III, W.W.: 1972, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Universe Books, New York.
40. Bloomfield, B.P.: 1986, *Modelling the World: The Social Constructions of Systems Analysts*, Basil Blackwell, Oxford.
41. Cole, H.S.D., et al., Eds., 1973, *Models of Doom: a Critique of The Limits to Growth*, Universe Books, New York.
42. Forrester, for example, recommended reducing the world food supply, since in his view allowing it to increase would only support continued population growth, leading to worse famine later on. The hip, charismatic Dennis Meadows was widely viewed as more a media personality than a serious scientist.
43. King, A.: 1981, 'The Club of Rome and Its Policy Impact,' *Knowledge and Power in a Global Society*, W.M. Evan, Ed., SAGE Publications, Beverly Hills pp. 205-224.
44. Meadows, D., Richardson, J., and Bruckmann, G.: 1982, *Groping in the Dark: The first decade of global modelling*, John Wiley & Sons, New York.
45. Mesarovic, M. and Pestel, E.: 1974, *Mankind at the Turning Point*, Signet Books, New York.
46. Hughes, B.B.: 1981, *Global Modeling*, Lexington Books, Lexington, MA.
47. Humphrey, C.R. and Buttel, F.R.: 1982, *Environment, Energy, and Society*, Wadsworth Publishing Co., Belmont, CA.
48. Lempert, R., Schlesinger, M., and Hammitt, J.: 1994, 'The Impact of Potential Abrupt Climate Changes on Near-Term Policy Choices,' *Climatic Change* **26**, 351-376.
49. Schlesinger, M. and Jiang, X.: 1991, 'A Phased-In Approach to Greenhouse-Gas-Induced Climatic Change and Climatic Response to Increasing Greenhouse Gases,' *Eos Transactions of the American Geophysical Union* **72**, 596-597.
50. Lindzen, R.E.: 1992, 'Global Warming: The Origin and Nature of the Alleged Scientific Consensus,' *Regulation – Cato Review of Business & Government*, Spring issue, 87-98.
51. Lindzen, R.S.: 1990, 'Some Coolness Concerning Global Warming,' *Bulletin of the American Meteorological Society* **71**, 288-299.
52. Schneider, S.H.: 1987, 'An International Program on "Global Change": Can It Endure? – An Editorial,' *Climatic Change* **10**, 211-218.
53. Liverman, D.: 1987, 'Forecasting the Impact of Climate on Food Systems: Model Testing and Model Linkage,' *Climatic Change* **11**, 267-285.
54. Donoghue, J.: 1994, 'International Law and Policy-Making about Global Change,' *Ecological and Social Dimensions of Global Change*, D.D. Caron, F.S. Chapin III, J. Donoghue, M. Firestone, J. Harte, L.E. Wells, and R. Stewardson, Eds., Institute of International Studies, Univ. of California, Berkeley, Berkeley, CA, pp. 273-295.
55. Noll, R.G. and Cohen, L.R.: 1988, 'Economics, Politics, and Government Research and Development,' *Technology and Politics*, M.E. Kraft and N.J. Vig, Eds., Duke University Press, Durham, NC, pp. 123-139.
56. At this writing the EPA faced a probable $1 billion cut, about one-sixth of its current annual budget, in FY 1996, and Congress was moving to de-fund US participation in Montreal Protocol enforcement. In the face of measures like these, it is difficult to imagine Congress approving *any* large-scale, comprehensive regulatory policies.
57. However, some economic policies which initially appear as costs may in fact produce medium-term direct benefits (e.g. energy efficiencies) unrelated to climate. See L. Goulder: 1994, 'The Economic Impact of Preventing Global Change,' *Ecological and Social Dimensions of Global Change*, D.D. Caron, F.S. Chapin III, J. Donoghue, M. Firestone, J. Harte, L.E. Wells, and R. Stewardson, Eds., Institute of International Studies, Univ. of California, Berkeley, CA, pp. 273-295.
58. McDougall, W.A.: 1985, *The Heavens and the Earth: A Political History of the Space Age*, Basic Books, New York.

59. Schneider, S.H.: 1989, *Global Warming: Are We Entering the Greenhouse Century?*, Vintage Books, New York.
60. Keohane, R.O., Haas, P.M., and Levy, M.A.: 1993, 'The Effectiveness of International Environmental Institutions,' *Institutions for the Earth: Sources of Effective International Environmental Protection,* P.M. Haas, R.O. Keohane, and M.A. Levy, Eds., MIT Press, Cambridge, MA, p. 14.