You may know the joke about the drunken sailor who tries to find his key in the cone light of the street lamp because of the darkness at the place where he lost it. I wonder, if economists don't behave in the same manner when they monetize the increase in electricity consumption for air conditioning due to higher temperature, and do not monetize the social costs of sudden catastrophes and armed conflicts due to lack of data? The key for solving the climate change problem, I am afraid, must be found in a different way.

Thank you very much for your attention.

Gary W. Yohe

Integrated Assessment of Climate Change – the Next Generation of Questions

Future historians who will track the course of human interaction with the environment will, in all likelihood, mark 1997 as a watershed year. The frenzy of activity building across the globe in preparation for the Third Conference of the Parties (TCOP) of the Framework Convention on Climate Change (FCCC) has, if nothing else, brought global environmental change to the front of the global policy stage; and it is difficult to see how and why it will ever retreat from that prominent spotlight. Indeed, the Intergovernmental Panel on Climate Change (IPCC) hardly took a breath between the completion of the Second Scientific Assessment and the initiation of the Third. Informed by collaboration by Dr. Hans Joachim Schellnhuber and his colleagues at the Potsdam Institute for Climate Impact Research (PIK) in Potsdam, Germany (see Schellnhuber/Yohe 1997) as well as collaboration with other colleagues from the Center for the Integrated Assessment of the Human Dimensions of Global Change located at Carnegie Mellon University, from the Kennedy School of Government at Harvard University, and frankly from around the world, I would like to propose that the climate research community can make 1997 a watershed year of equal importance for future historians of science – but *not if we move forward over the next ten years by offering more of the same brand of integrated assessment that has emerged over the past ten years*. We must take the time even as we try to support the policy debate leading up to the TCOP in Kyoto to review critically the integrated assessment work of the past decade; we must have the courage to acknowledge its shortcomings and to assess its potential; we must have the wisdom to draw socio-economic and political lessons from that potential; and we must identify questions whose answers will best inform the post-Kyoto decision process over the long term.

The paper that I offer to this Symposium is designed to make a modest step in this regard. It begins with a quick review of the economic efficiency criteria that most of policy motivated integrated assessment efforts to date have adopted – a review from which much of the news is not good. The information required to characterize an efficient long term mitigation response to the threat of global climate change is staggering, and so optimization results must be interpreted with a wary eye towards what is practical as well as what is politically palatable. All of the news is not bad, though. Section II looks at the results of existing integrated assessment efforts from a broader perspective and finds that significant progress in understanding a wide variety of less holistic but nonetheless integrated issues has been made. Indeed, Section III summarizes some of this progress into five general lessons and frames series of questions around their content that are designed to advance not only the science and social science of global change, but also the political science of the fundamental policy issue: designing effective short-term mitigating policies that can meet fundamental long-term goals on a global and constructing the international political structures that can sustain their implementation and enforcement at more regional and national levels. Concluding remarks in Section IV offer some contextual encouragement that these are, indeed, questions that must be answered before the stakes get too high.

I Integrated Assessment of Climate Change – Foundations for the First Generation of Questions

While several analyses of some of various issues related to global climate change predate its publication, it is widely agreed that the first attempt to present an integrated analysis of the complete global system from a policy perspective was authored by William Nordhaus in 1991 (see Nordhaus 1991). His question, "To slow or not to slow?", framed much of the subsequent research by embracing dynamic economic efficiency as the overarching decision criteria and casting the problem in terms of the economists' traditional cost-benefit framework. Inspired by his seminal contribution, much of the integrated assessment work that followed has focused on refining estimates of the requisite functional relationships between control costs and reductions in greenhouse gas emissions from unrestricted baselines, on the one hand, and between the potential cost of climate change and change in the global mean temperature, on the other.

Figure 1 displays the standard cost-benefit framework in its simplest form. It highlights the efficient solution to the question of optimal emissions reduction at the intersection of a climbing schedule that reflects the marginal cost of emissions reduction from a baseline and a declining schedule that tracks the associated marginal benefits of those reductions (i. e., the value of damages avoided). To stop emissions reduction below that intersection would be to forego additional reductions for which the benefits would outweigh the cost; but to go beyond the intersection would involve paying incremental costs in excess of any benefit that might be forthcoming. The solution also quantifies the "shadow price" of emissions – the value of the last small reduction in emissions *and* the emissions tax that would support optimal reductions from profit maximizing (competitive) emitters.

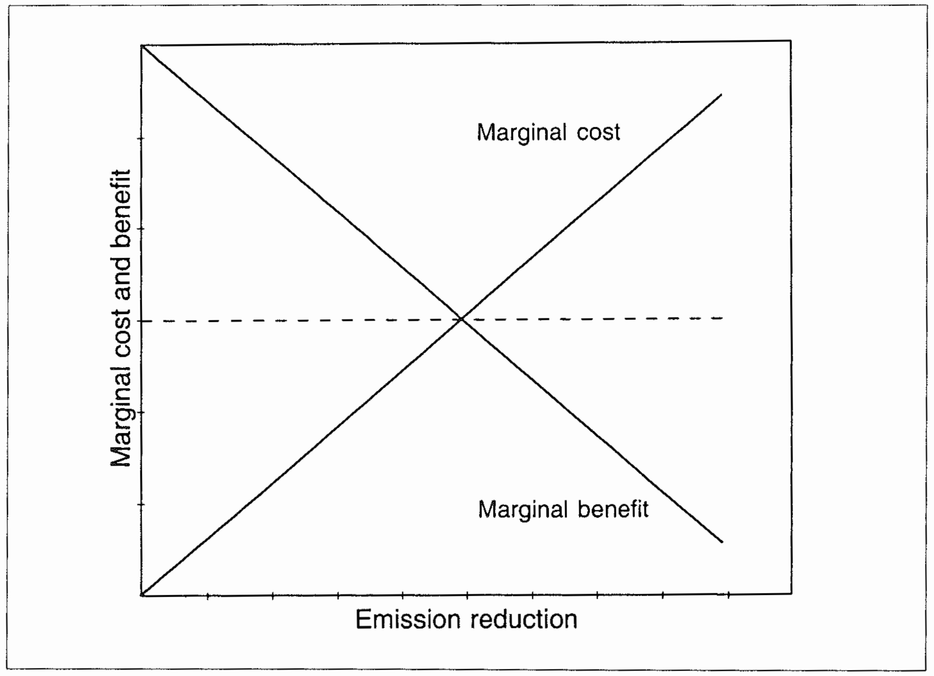

Fig. 1
Standard cost-benefit efficiency framework

The portrait of the efficiency paradigm offered by Figure 1 hides an enormous amount of complication. Economic efficiency, for example, essentially ignores distributional issues by assuming, in effect, that the optimum produces so much economic surplus that those who benefit from the analyzed change in economic circumstance can and will compensate fully those who suffer and associated losses. It has become obvious as the negotiations for a global mitigation policy have progressed that this is a difficult assumption to swallow in the climate change arena. More fundamentally, however, focusing on the cost-benefit paradigm has drawn the research community further and further from questioning whether or not long-term dynamic optimization is the most productive way to frame the policy problem. Distributional issues aside, applying the efficiency criterion to the long term policy question requires volumes of information that we may never possess. It is, therefore, time to expend less effort reviewing modest progress towards quantifying the marginal cost and benefit schedules, themselves and to expend more effort questioning whether we will ever have sufficient confidence in their quantification to believe the efficiency results?

Figure 2 offers a different portrait of the underlying structure of the cost-benefit paradigm applied to a long-term dynamic context like global climate change that more accurately reflects the complexity of describing intertemporal efficiency. Two alternative future trajectories are displayed there. The first, labeled "unrestrained", tracks a welfare or utility measure that climbs over time at a decreasing rate to reflect the declining marginal welfare attributable to the output of expanding economic activity net of the cost of increased environmental degradation in the absence of any environmentally motivated restraint. The second tracks the same welfare measure when damaging emissions are marginally reduced in the near-term (the scale of the reduction is exaggerated so that the difference in the two trajectories is discernible). The "restrained" trajectory falls below its unrestrained baseline over the near-term because the cost of emissions reductions must be borne when they are incurred and because part of their cost is reduced investment in the productive capacity that required to sustain the baseline; but it runs above the unrestrained baseline in the more distant future because emissions reductions ultimately have some long-term environmental benefit. The two paths may or may not converge over time, but that is irrelevant. The cost-benefit paradigm, applied to the dynamic context depicted in Figure 2, weighs the *discounted value* of annual benefits derived far in the future from *emissions reduction from the baseline* against the *discounted value* of annual costs of those reductions that are incurred in the less distant future – **and it does this for each and every incremental reduction in emissions from the baseline that might be contemplated at each and every point in the future**. The dynamic solution, finally, holds that emissions *at each point of the future* should be reduced to a level where the discounted value of the cost of last ton *not* emitted at that time equals the discounted value of the future benefits generated by that last unit of foregone emissions *for each and every year along the entire trajectory.*

Armed with this characterization, it is now possible to characterize just how much information is required to quantify fully the optimal dynamic solution to the Nordhaus question. Figure 2 highlights four areas with arrows where these requirements can be productively described. The arrow labeled "A", for example, focuses attention on the unrestrained baseline trajectory which must, of course, be completely described. All of the driving variables of economic activity must be known; and their role in supporting economic activity must be modeled fully in a way that incorporates accurately the changing political, social and cultural landscapes of all relevant

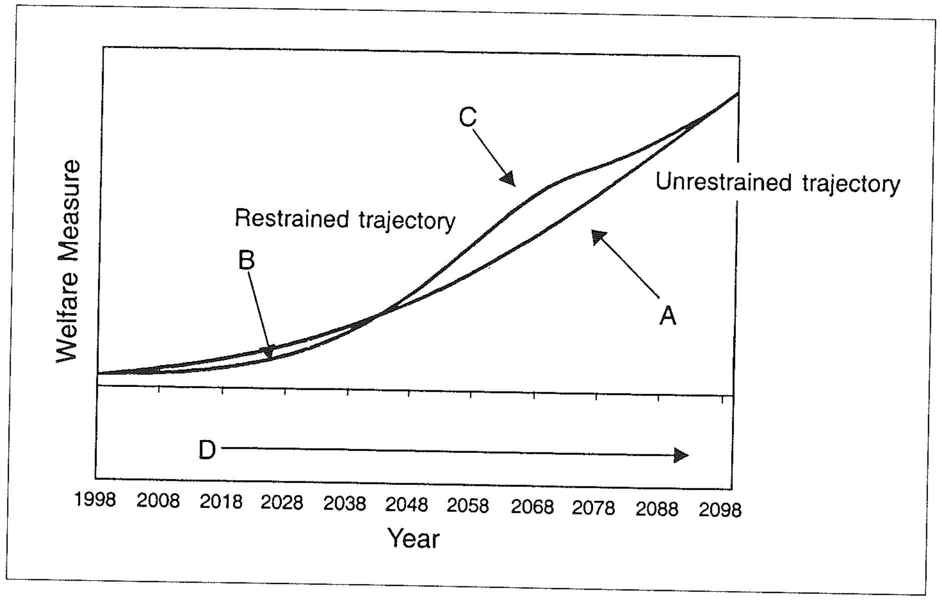

Fig. 2
Alternative welfare trajectories

national, regional, and global societies. All of the environmental impacts must be quantified, as well; and those impacts must be captured by the welfare measure in ways that reflect accurately how individuals living in changing societies will adapt to changes in their physical environment and how the cost of that adaptation will be distributed. Arrows B and C divide the restrained trajectory into two distinct parts – the first where the cost of emissions reduction are felt more heavily, and the second where the incremental benefits finally outweigh the residual costs. Both can be thought as deviations from the baseline, but both require something more than a specification of that baseline. Quantification of region B requires, in addition to an accurate portrait of the baseline, an equally accurate representation of the distribution of the cost of emission reduction net of any adaptation to that reduction that will be forthcoming but including the cost of that adaptation. Depiction of region C requires models that portray the distribution of the benefit of emission reduction from the baseline, net of the cost of adaptation that is no longer required. Arrow D, finally, highlights the intertemporal issues that embrace the entire question along both trajectories – issues of economic discounting across generations and geographical boundaries, atmospheric discounting of greenhouse gas concentrations across the spectrum of damaging emissions, pervasive uncertainty, and the potential for surprises.

A quick review of the Program for this Symposium can bring the enormity of the requirements associated with each of these arrows into clearer focus. Table 1 sorts each of the contributions to a remarkably comprehensive science program according to which arrow or arrows might be informed by research in each highlighted subtext (each of the preceding contributions is identified by author and by session number with "K" or "C" differentiating between keynote and complementary lectures). Notice that support of arrow B, the designation for analysis into cost and distributional issues involved in designing and implementing mitigation policy, is missing from the Program. Support of arrow D, notation for intertemporal issues involving discounting, uncertainty and surprises, is sparse; so, too, is support of the social science designed to construct trajectories of the drivers of global change. Support for many of the impacts components involved in specifying the both the environmental consequences of the baseline and the potential benefit of mitigation is more adequately covered. The point of making these distinctions is not to criticize the Program; there is only so much that can be accomplished in any one Symposium and there is a limit to how much we know. It is, instead, to allow the stark observation that a complete solution to the dynamic efficiency question posed by Nordhaus would require (1) **complete resolution of all of the uncertainties and outstanding scientific issues raised throughout the Program** *and* (2) **complete resolution of all of the uncertainties and outstanding social and economic science issues that are missing** – a daunting task, indeed.

Arrow represented in figure 2			
A	**B**	**C**	**D**
1K Hasselmann		1K Hasselmann	6K Bengtsson
1C Rahmstorf		1C Rahmstorf	6C Berz
2K Crutzen		2K Crutzen	7K Tol
2C Schulze		2C Schulze	7C Müller
3K Herterich		3K Herterich	
3C Kemp		3C Kemp	
4K Bárdossy		4K Bárdossy	
4C McMichael		4C McMichael	
5K Prentice		5K Prentice	
5C Hempel		5C Hempel	
7K Tol		7K Tol	
7C Müller		7C Müller	

Tab. 1
Topical Support of Integrated Assessment

II Integrated Assessment of Climate Change – Insights from the First Generation of Questions

The gloom that hangs over the first section of this paper must not be interpreted to mean that all of the effort that has been expended thus far in analyzing climate change has been wasted. Researchers from around the world have been grasping to find instructive answers to policy issues given the current state of our understanding of the integrated climate system, and some of their results have proven to be remarkably robust. Perhaps more importantly, working the problem has allowed the community to begin to discover not only which questions are tractable with current methods (and which are not), but also which answers are most likely to enhance most significantly our ability to choose a desirable future. This section will offer a brief review of the progress. The reader is warned, however, that the discussion that follows has been designed less to be comprehensive and more to be uncover the next most productive set of questions for future research. The interested reader is referred to IPCC 1996, to Rotmans et al. 1997, to Weyant 1997, to Tol/Fankhauser 1997 or to papers published by the researchers themselves for more thorough coverage of the particulars that have been omitted.

Table 2 highlights most of the major integrated assessment efforts that are currently underway. The first column records the acronym by which each integrated assessment model is known while the second lists its principal developer(s). The first column also provides at least one reference for each model – not necessarily the most recent publication, but one in which the structure of the model is described in some detail. The last three columns give some insight into those structures. The third column, for example, offers a rough typology for sorting the listed models. The categories are meant to be suggestive only of the original intent of the modelers, and they are not, in practice, mutually exclusive. Five models are designated DMUM indicating that they were designed most explicitly to *accommodate* uncertainty. The other sixteen are deemed to be *deterministic* in nature, indicating that they were designed either to uncover an optimal mitigation policy (DPOM) or to explore the properties of a variety of specific policies along specific baseline scenarios of how the future might unfold (DPEM). Several of the optimization models have, of course, been employed to conduct second-best analyses of the sort targeted by the creators of evaluation models; and thirteen of the models listed in Table 1 have been employed to conduct uncertainty analysis of one sort or another.

The fourth column of Table 2 records a characterization of the spatial resolution of each model. It is clear that the twenty-one models surveyed here span a wide spectrum. Seven take a global perspective, three look to describe climate change within grids as small as 0.5 square, and the remaining eleven divide the global into two to eleven distinct regions. The final column highlights how the potential damage associated with climate change is included in each model. Nearly 50 % of the models use one or two aggregated reduced form equations to reflect monetary damage as a function of (usually) change in global mean temperature; and even the models that offer sector representations rely fundamentally on reduced form representations of monetary damages derived from a severely limited vector of climate change parameters.

Table 2 certainly suggests that models and modeling approaches differ widely, but modeling diversity is not fully represented even there. As suggested in the qualitative description of the requirements embodied in arrows A and B of Figure 2, modelers who offer regional portraits need to worry about how those regions interact economically, socially, and politically. Others who offer smaller grid portraits need to worry about how those grids aggregate into countries and regions. Modelers with only a global perspective can avoid all of that complication, but they need to worry about how to aggregate local and regional effects into reduced form representations that apply globally. Most models integrate spatially by linking economies with trade, and so they are dominated by economic constructions. A few, however, integrate according to physical changes in non-economic indices like land use, land cover, and/or ecosystem sustainability. In such cases, economic considerations and political boundaries can still be important, but aggregation and valuation techniques need not rely at all on units of currency. Models also differ in their treatment of technological progress because modelers need to decide the degree to which progress is autonomous and, conversely, the degree to which it can induced by the economic consequences of climate change and/or climate change policy. Modelers must, as well, make assumptions about the forecasting capacity of the decision makers that inhabit their models and their abilities to cope uncertainty by locating credible information; and they must describe how a large suite of non-environmental policies will evolve as the future unfolds.

Given this diversity in modeling approach, it is perhaps surprising that a number of remarkably robust conclusions have been drawn from the existing work. The most striking, perhaps, comes from many of the models that adopt the dynamic optimization criterion. Weyant (1997) has observed that they generally show that only modest control is warranted over near- and medium-term policy horizons. Indeed, most optimal carbon "taxes" start low ($5 to $15 per ton of carbon in the near-term) and climb slowly over the next century (reaching $50 to $100 per ton by 2100) so that emissions of greenhouse gases continue to grow (at a reduced rate

Model Acronym (reference)	Principal Developers	Typology[a]	Spacial Scale[b]	Damage Representation
AS/ExM (Lempert et al. 1994 and Lempert et al. 1996)	Robert Lempert/Steve Popper (Rand), Michael Schlesinger (U of Illinois)	DMUM	global	1 reduced form equation
AIM (Morita et al. 1994)	T. Morita, M. Kainumn (NIES, Japan), Yuzuri Matsuoka (Kyoto U.)	DPEM	½° × 1½° grid	sectoral models
CETA (Peck and Teisberg 1992)	Stephen Peck (EPRI), Thomas Teisberg (Teisberg Assoc)	DPOM	global	1 reduced form equation
Connecticut (Yohe and Wallace 1996)	Gary Yohe (Wesleyan University)	DPOM/ DPEM	global	1 reduced form equation
CSERGE (Maddison 1994)	David Maddison (U. College of London)	DPOM	global	2 reduced form equations
DIAM (Grubb et al. 1995 and Grubb 1997)	Michael Grubb, M. H. Dong, T. Chapius (Royal Institute of International Affairs)	DPOM	global	1 reduced form equation
DICE (Nordhaus 1994)	William Nordhaus (Yale Univ.)	DPOM	global	1 reduced form equation
FUND (Tol 1995)	Richard Tol (Vrije Universiteit Amsterdam)	DPOM	nine regions	reduced form by sector
HCRA (Hammitt et al. 1995)	Jim Hammitt (Harvard), Atul Jain/Don Wuebbles (U. of Illinois)	DPOM	one or two regions	reduced form with catastrophes
ICLIPS (Toth et al. 1997)	Gerhard Petschel-Held, Hans-Joachim Schellnhuber, Ferenc Toth (PIK) and an international consortium	DPEM/ DPOM	multiple regions	sectoral models
ICAM-2 (Dowlatabadi and Morgan 1993)	Hadi Dowlatabadi (Carnegie Mellon), Granger Morgan (Carnegie Mellon)	DMUM	seven regions	sectoral models

[a] Notationally, DPOM = Deterministic Policy Optimization Model; DPEM = Deterministic Policy Evaluation Model; and DMUM = Decision Making Under Uncertainty Model.

[b] Adapted from Tol/Frankhauser 1997.

Tab. 2
Integrated Assessment Models (adapted from Table 1 and Figure 2 of Weyant 1997)

Model Acronym (reference)	Principal Developers	Typology[a]	Spacial Scale[b]	Damage Representation
IMAGE 2.0 (Alcamo 1994)	Joe Alcamo, M. Janssen, M. Krol (RIVM, Netherlands)	DMUM	½° grid	several models
MARIA (Mori 1995)	Shunsuke Mori (Sci. Univ. of Tokyo)	DPOM	four regions	1 reduced form equation
MERGE 3.0 (Manne et al. 1995)	Alan Manne (Stanford), Robert Mendelsohn (Yale), Richard Richels (EPRI)	DPOM	nine regions	2 reduced form equations
MiniCAM (Edmonds et al. 1994)	Jae Edmonds (Pacific Northwest Lab) Tom Wigley (UCAR), Richard Richels (Electric Power Res. Inst)	DPOM	eleven regions	sectoral models
MIT (Yang et al. 1996)	Henry Jacoby/Ron Prinn (MIT), Zili Yang (MIT)	DPEM	eleven regions	sectoral models
PAGE (CEC 1992 and Plambeck and Hope 1996)	Chris Hope (Cambridge Univ.), John Anderson/Paul Wenman (Env. Res.)	DMUM	seven regions	reduced form by sector
PEF (Cohan et al. 1994)	Joel Scheraga/Susan Herrod (EPA), Rob Stafford/Nathan Chan (DFI)	DMUM	two	sectoral models
RICE (Nordhaus/Yang 1996)	William Nordhaus (Yale Univ.), Zili Yang (MIT)	DPOM	six regions	1 reduced form equation
SLICE (Kolstad 1993 and Kolstad 1994)	Charles Kolstad (Univ. California Santa Barbara)	DMUM	global	1 reduced form equation
TARGETS (Rotmans et al. 1994)	J. Rotmans (RIVM), M. Janssen (RIVM), H. J. M. de Vries (RIVM)	DPEM	varied and detailed	sectoral models

[a] Notationally, DPOM = Deterministic Policy Optimization Model; DPEM = Deterministic Policy Evaluation Model; and DMUM = Decision Making Under Uncertainty Model.

[b] Adapted from Tol/Frankhauser 1997.

Tab. 2, continued
Integrated Assessment Models (adapted from Table 1 and Figure 2 of Weyant 1997)

relative to the baseline) over time. Why? As portrayed by the restricted trajectory of Figure 2, most models of any type relate the cost of emissions reduction to the current emissions rate. As a result, the cost of emissions reductions begin with the onset of the policy. The impacts of climate change are, meanwhile, usually related to atmospheric concentrations which are, themselves, modeled to depend upon cumulative emissions. Current emissions therefore effect the modeled climate system with a significant lag so that the benefit of the immediate cost of near-term emissions reduction is delayed (and discounted in DPOM approaches where the return to investment in near-term emissions reduction is compared with investment in other projects whose greater returns could underwrite more vigorous emissions reductions in the future). Placed in the context of the debate that has been leading to the TCOP, it should be noted that none of the efficiency models conclude that stabilizing emissions at anything like 1990 levels would be dynamically optimal on two counts. None, first of all, come close to supporting the roughly 60 % reduction in greenhouse emissions that would be required to constrain greenhouse gas emissions at 1990 levels by 2010 against the IPCC IS92a baseline. Indeed, Yohe et al. 1998 argue that the damage associated with 2.5 °C warming would have to exceed 9 % of global GDP to support fixing emissions at 2010 levels, and only if unrestricted emissions would run much higher than the IS92a trajectory. In addition, none generate optimal trajectories that fix emissions over long periods of time at any level. The current popular view that emissions must be fixed at some predetermined level is therefore a decidedly second-best policy alternative

It cannot be asserted, though, that support for only modest near-term mitigation is unanimously supported by the DPOM community. Grubb et al. 1995 is representative of a group of dissenting researchers who argue that there is significant inertia in economic infrastructure. They conclude, as a result, that the technological advances required to effect larger emissions reductions in the future will occur only if it is induced by restrictive near-term policy; but this is never a low-cost option. Indeed, the very inertia that speaks for the need for ambitious near-term response also speaks to the size of the „economic stick“ required to change things for the better.

The same debate about technological change has also arisen within the DPEM community where many models have suggested that the cost of achieving specific concentration limits can be reduced dramatically by allocating emissions reductions efficiently across space and time (see, most notably, Wigley et al. 1996). Spatial efficiency asserts that the *least cost* source of emissions reduction always be exploited, *regardless of its location*. Temporal efficiency, meanwhile, asserts that emissions reduction exploit intertemporal investment opportunities to maximize economic growth given the modeled lags in the climate system; *exploiting those opportunities simply works to “buy time” before more rigorous emissions reduc-*

tions are required. Again, these are opportunities that work well only if emissions-saving technologies evolve over the intervening years. Some modelers believe that these technologies can be encouraged even in the absence of near-term mitigation (by, say, underwriting the cost of research and development in energy-saving technology), but others like Grubb (1997) and Dowlatabadi (1997a) hold that they will *not* emerge if they are not induced by vigorous and virtually immediate intervention.

Adaptation to stresses caused by change in any environment certainly plays a role in any credible policy evaluation of how to cope with that change, and the climate-policy arena is no exception. Indeed, there are two fundamental sources of stress that must be recognized: climate change, itself (arrows A and C of Figure 2), *and* any policy that might be imposed to mitigate against that change (arrow B). A case can be made that most of the existing models have captured at least some part of the efficiency side of responding to climate change policy. Some have very detailed energy sectors and so they can incorporate specific new technologies for delivering energy across the globe at a reasonable price into their portraits of how the future might unfold in response to a specific mitigation policy. Others are very aggregated, but they can still accommodate adaptation to climate policy by looking at the shadow-price equivalent of any policy and properly specifying economic parameters such as the elasticity of substitution between various energy types. While the debate over induced or autonomous technological change also suggests that there is more work to be done in this area, it is also clear that estimates of the cost of climate policy are far better at including the *potential for adaptation* than are estimates of the potential benefits of such policy.

The last column of Table 2 makes this point implicitly by noting that most models reflect damages in reduced form equations. There is, therefore, little hope that adaptation can be captured in most existing models by anything more sophisticated than adjusting their calibration of (e. g.) the anticipated cost of a doubling of the atmospheric concentration of greenhouse gases. Would a more careful inclusion of adaptation on the benefit side make a difference? That remains to be seen, but some strong evidence to the affirmative is starting to emerge. Estimates of the cost of sea level rise along the developed coastline of the United States fell, for example, by nearly 90 % when they moved from measuring vulnerability (the current value of property threatened by rising seas) to measuring market-based economic costs that included efficient decisions to protect or abandon specific pieces of property at a very micro level (see Yohe et al. 1997). Subsequent work has suggested that the market response mechanism might not work to its optimum under natural and policy uncertainty, especially when stochastic events like coastal storms are included in the analysis. The lower estimates of true economic cost might therefore be off by a factor of two (see West, et al. 1997); but they would still be more than 70% lower than the earlier vulnerability statistics.

The magnitude of the sensitivity of damage estimates to adaptation may not always as large as it is in the sea level case for developed economies, but a general pattern seems to be emerging from the second generation of impacts assessments (see, e. g., Mendelsohn/Neumann 1999): people and the social, political and economic institutions that they create will adapt to climate change, and this adaptation can be expected to reduce the cost of that change *even when the cost of adaptation is added to the equation*. Increasing care needs to be taken, therefore, to investigate the conditions under which it will be important to know how people might adapt. It will be important to understand, for some vulnerable sectors, who would know what along any scenario of how the future might unfold. We will need (i) to understand the mechanism by which they would learn about the change that that scenario would bring, (ii) to envision where they would turn for credible information, (iii) to judge when they would believe that information, (iv) to anticipate what they would do with it; and so on. For other sectors, answers to these questions might be insignificant in the grand scheme of things, and so their pursuit would be pointless. In still other sectors, context and structure might so complicated that it will be impossible to answer even one of these questions, and so an alternative method for contemplating adaptation might be required. These are, of course, issues for the impacts community as they allocate their scarce energy and funding; but integrated assessment modelers must also recognize their importance and the limitations that they impose on our ability to quantify damage functions as they refine their existing models and, more importantly, *as they contemplate the next set of questions to be analyzed*.

Any consideration of climate change concludes almost immediately that uncertainty is ubiquitous; this is one of the points underlying arrow D of Figure 2. Uncertainty permeates our understanding of the entire climate system, starting with the drivers of anthropogenic greenhouse gas emissions, cascading through the science of atmospheric interactions of those gases with the oceans and the biosphere, and spilling through the impacts of those interactions on natural, social, political, and economic systems. This observation is obvious, of course, and it is reassuring that it has not been lost on integrated assessment modelers. Table 3, adopted from Kann 1997, lists thirteen models that were identified in Table 2 and whose developers have tried to incorporate uncertainty into their analyses to some degree. The second column highlights the sources of uncertainty that they have explored, and the third column records summaries of what the authors see as the key result(s) that their work has produced.

The results are, as one would expect, varied; but there are, again, a few general insights to be drawn from the collective efforts of many different modelers. First of all, anticipating that the globe might be moving along an unexpectedly rapid but nonetheless smooth climate change trajectory does little to alter the qualitative assess-

Model	Which uncertainties?	Key result
AS/ExM	climate sensitivity, damages from temp. change, abatement cost reduction	Best-estimate policies incur large costs relative to optimum policy if state of the world turns out to be different from what was assumed by best-estimate policy. Choice between best-estimate policies is strongly dependent on society's expectations about all three uncertainties. Ability to make midcourse corrections proves very valuable.
CETA	warming per CO_2 doubling, level in damage function, power in damage function	The benefit of resolving uncertainty in optimal policy is high, but resolving uncertainty sooner rather than late is not worth much. If an arbitrary political policy is used, and if resolving uncertainty soon would imply that an optimal policy would be used, then resolving uncertainty sooner rather than later pays dividends.
HCRA	climate sensitivity, economic cost of mitigation, climate target delta T.	Value uncertainties may be more salient for policy choice. Policies that are sequentially revised as new information becomes available may be superior.
DIAM	stochastic stabilization limit, impact costs	Possibility of low levels of stabilization limits has large influence on optimal path (even though this occurs with low probability). Consideration of impact costs leads to different time profiles than optimization under a stabilization constraint (fixed or stochastic).
DICE	rate of population growth, productivity growth, discount rate, GHG-output ratio, damage function intercept, climate-GHG sensitivity, mitigation cost fctn. intercept, atmospheric retention	Carbon tax might be more efficient instrument in light of enormous uncertainties. Carbon tax is more invariant across resolution of uncertainties than optimal GHG control rate. Information can help understand how investments of resources to obtain better in formation about the future climate and social sciences can pay off.
FUND 1.5	Selected parameters, including: socio-economic drivers, carbon cycle/ climate, climate change impacts, emissions reduction	The business as usual scenario leads to an unbounded loss when uncertainty is included (though the divergence is slow). This does not occur with the emissions reduction scenarios. Optimal emissions reduction is more strict under uncertainty than under certainty. Under uncertainty, there is no emission trajectory that avoids risk of both severe costs of emission reductions and severe impacts of climate change.

Tab. 3
Uncertainty in Integrated Assessment Models (adopted from Kann 1997)

Model	Which Uncertainties?	Key Result
ICAM-2	parameters (up to 25), decision rules and metrics, model structure	Optimal decision depends on the decision rule. None of the policies are stochastically dominant.
MERGE 2.0	high-damage and low-damage scenario.	With a small chance of high damages, a hedging strategy departs only slightly from the low-damage case. Hedging strategy is sensitive to date at which uncertainty is resolved.
PAGE 95	80 uncertain parameters: scientific, costs of control and adaptation, valuation of impacts	Important factors come from all four groups of inputs to the model. Most important parameters are preventive costs of CO_2 and temperature sensitivity.
PEF	scenario specific	Uncertainty in impacts may be as important as uncertainty in climate change. Adaptation policy could have larger effects on impacts more quickly. Mitigation is less effective when adaptation is high.
SLICE	climate damage	The irreversibility of investment capital has a stronger effect than irreversibilities in climate change; un-certainty and learning tend to bias emission control downward.
TARGETS	CO_2 fertilization, soil moisture changes, migration of ecosystems, temp. feedback on vegetation, temp. feedback on production, sulphate aerosols, water vapor, clouds, policy measures	Takes into account a variety of perspectives in relation to uncertainty, which allows for rendering subjective judgment explicit.
CONNECTICUT	population growth, technological change in energy supply, depletion factor in fossil fuel price, interfuel elasticity of substitution, others that play less significant roles in the distribution of emissions	Little emissions reduction warranted over the near term even as a hedge against meeting severely binding concentration limits in the not too distant future. Modest emissions reduction can be supported as hedges against high consequence/low probability events. Hedging to achieve "tolerable windows" proposed by German Advisory Board on Climate Change might require significant near term emissions reduction.

Tab. 3, continued
Uncertainty in Integrated Assessment Models (adopted from Kann 1997)

ment of dynamically efficient long-term policy. Slightly more vigorous near-term mitigation effort might be appropriate in such a case, but it would still be modest – still falling well short of stabilizing emissions at current or historic levels especially if more rapid change were driven by more energetic economic activity. Even near-term hedging against the realization that future climate change might turn out to be much more damaging than expected offers little reason for dramatic intervention over the next several decades.

Support for modest near-term policy can erode significantly, though, if models reflect the possibility that the future might *not* bring a smooth transition from one climate state to another. Even though small chances of high consequence events offer unexpectedly small incentive for adjusting near-term hedging strategies in favor of more robust mitigation, highlighting their potential for catastrophic and irreversible climate change suggests that policies whose goal is to satisfy long-term dynamic efficiency conditions might be the right answers to the wrong questions. A few analysts have begun to investigate the near-term implications of designing mitigation strategies that can be adjusted over time as we learn more about the size and pace of climate change and its impacts. This has lead some to look for robust near-term polices that minimize the expected cost of being wrong during the learning process (see, e. g., Lempert et al. 1996). It has lead others to consider hedging in the near-term across the potential for widely disparate emissions trajectories *and* against the potential that climate change will move beyond a "tolerable" target before we have a chance to judge precisely what that target should be (see, e. g., Yohe 1997). The results of these exercises are less important than the issues that they raise – issues that sound hauntingly like the issues now confronting the impacts community. How will we learn about climate change? How should we set near-term policy to maximize the pace of that learning? When might we learn that future climate change will or will not be smooth when there is so much natural variability in the climate system? When will we be more certain that climate change will proceed rapidly, or slowly, or variably into the future? What sort of monitoring mechanisms should be created so that policy can respond to new understanding that will always be clouded by noise? How do we set climate policy targets that are meaningful, feasible, and flexible? Should the targets be specified in emissions, concentrations, temperature change, the rate of temperature change, or what? How do we create mechanisms so that we can minimize the cost of meeting those targets *and* minimize the cost of making adjustments as the future unfolds? How sensitive are these costs to the specification of the targets? How much short-term variability should be allowed as the globe moves to meet interim policy targets along long-term trajectories?

III Integrated Assessment of Climate Change – the Next Questions.

I argued in the first paragraph that pressure placed on the research community by the impending Kyoto meeting has certainty combined with the start of the Third Scientific Assessment by the IPCC to produce an imperative that we take stock of what we have learned over the past few years and try to judge where we might most effectively focus our attention over the next few. This section will offer some thoughts that are informed by some of the most general lessons that can be drawn from past work. It will build from the foundation described briefly above, and it will try to provide some organization to the litany of specific questions listed there. Table 4 offers a synopsis of the questions that emerge, but the reader is encouraged to consult the text to see how each is related to the lessons of the past decade.

Lesson 1: Policy Design Matters.

The integrated assessment research community and all of its "clients" must come to the grips with the fundamental truth that *policy design matters critically in the determination of how the globe will respond to anthropogenic climate change.* Researchers of every stripe must come to understand that different policies can have dramatically different consequences in terms of their effectiveness, enforceability, equity, and economic cost effectiveness even though some might expect them to produce the same long-term effect on the climate system. They must come to understand the critical need to define mechanisms by with international policy can be adjusted over time as our knowledge-base improves. And researchers must, above all, recognize that the stakes are enormous and will only grow over time. Advocates of environmental protection must come to the same realization. They may want to discard the efficiency criteria (even if computing efficient solutions were tractable), and that is certainly within their prerogative; but it should be clear that less costly and/or more effective policies are more likely to draw wide democratic support than more expensive and/or less effective alternatives.

Assessment models must, therefore, begin to incorporate evolutionary processes if they are to be at all descriptive of how the future will, in fact, evolve. Even if we knew all there was to know about the climate system and its sensitivity to anthropogenic forcing, we would not be able to write mitigation and adaptation policy for the next century in 1998, 2008, or even 2018. We would still not know how that forcing would evolve through the year 2100, and so we could at best write contingency policies that would read the (then) historical record across a vector of economic, social and political variables and respond appropriately. We do not, of course, understand climate system at all well, either. The best that we can hope to achieve over time is an improved understanding of its sensitivity to forcing and correspondingly better means by which to monitor its important impacts. So armed, we will produce an evolving second vector of variables to which policy will be expected to respond. And if we accept this "muddling through" view of future climate policy, then we accept the notion that integrated assessment models must abandon the presumed omniscience of their actors in favor of analyzing informationally constrained response options.

To be more specific, the next generation of models needs to account explicitly for cognitive and voluntative development by looking at simulations that are, in fact, endogenously determined by the contingent decisions of their actors who gradually learn about what the future might bring in terms of economic, social, political and climatological events. This will lead not only to further integrated examination of impacts and implications, but also to new examinations of how actors learn and how efficient adjustments in policy might best be affected. Kolstad 1993, Lempert et al. 1996 and Yohe 1996 and others have made some initial attempts in this regard, but their work can be regarded as preliminary and provocative, at best. All of these authors worked with global models with a single reduced-form damage function, and so they missed all of the richness of learning and adapting to climate impacts noted above. Placing their work in the context of how the future will evolve nonetheless highlights several fundamental issues that can serve as unifying themes for *evolutionary* modeling. First, the primary policy focus should be on the near-term, but a primary objective must be preserving least-cost flexibility across a spectrum of possibilities over the long term. Secondly, careful attention must now be paid to creating mechanisms by which international policy can accommodate flexibility over the long term without causing a series of significant short-run disturbances in economic, social, and political systems; policy design (defining units, creating monitoring mechanisms, specifying sanctions for violation, assuring incentive compatibility, etc...) is essential. Thirdly, the targets of near-term policy and long-term flexibility must be defined in terms of impacts *cum* evolutionary adaptation that the global society will find "tolerable". Finally, the creation, flow and utility of accurate and credible information for both policy adjustment and adaptation will be critical; it may even be that the informational content of response to particular policy designs will be one of the primary objectives of effective near-term policy design.

Evolutionary approaches are capable of catching part of the intricacies of realistic integrated assessment of climate change. In particular, the outrageous requirement of perfect foresight of the secular coevolution dynamics of nature and civilization for the sake of precise cost-benefit analyses can be considerably relaxed. They cannot, however, provide remedy for the other fundamental problem of conventional cost-benefit analyses: the *offsetting* of genuinely distinct ecological, economic and social qualities affected by climate change. Even willingness-to-pay schemes will not succeed in converting the value of human lives or the raison d'être of ecosystems into, say, amenity units of driving a car, although large strides towards that goal have been made recently (see, e. g., Costanza et al. 1997).

One possible way out of this dilemma is the so-called "*guardrail approach*", which tries to reconcile a multitude of quality *standards* instead of optimizing a hypothetical scalar "utility-of-everything" function over the coming centuries. Dr. Schellnhuber will focus on some of the details of this approach in the next paper, but the basic strategy is easily stated: to confine climate development and its subsequent impacts to *tolerable corridors in multi-dimensional space* spanned by inconvertible key variables. The surfaces of these corridors provide guardrails for climate protection strategies to be selected by *expert-assisted democratic decision*.

The careful reader will notice that the evolutionary and guardrail approaches to integrated assessment are really quite complementary. Indeed, it is not difficult to imagine that global policy will "shoot at a moving target" over time with systematically varying degrees of intensity. More specifically, the intensity of the policy will be adjusted as we learn more about how the driving variables of climate change will actually "evolve" *and* the sensitivity of critical natural, social, economic and political systems to the borders of the "guardrails". As we turn our attention to future questions, the synthesis of the two approaches makes them obvious: how do we foster and sustain coordinated and timely assessment of

(i) the means and mechanisms by which climate policies can be adjusted,
(ii) the monitoring and dissemination of the information upon which those adjustments will be implemented, and
(iii) the definition of their respective targets?

The geographical distributions of both the potential cost of climate change and the burden of mitigating policy will play a fundamental role in this regard; and so three more questions emerge immediately:

(iv) How are the costs and major benefits of climate change and various policy options distributed?
(v) Upon what major state variables do those distributions depend?
(vi) How susceptible are those distributions to changes in the social, political, and economic condition of various nations and/or regions, especially if those changes are driven by non-environmental concerns?

Meanwhile, the economics of the requisite policies are well documented – adjustments to changing conditions must be smooth and, to some degree, predictable across the globe even if climate change, social pressures and political systems offer only a series of surprises. The political economy of how to build international institutions that can accommodate these sorts of adjustments is, however, not understood at all. And so:

(vii) What type of international regulatory mechanism can best handle the complication of an evolving global climate policy?
(viii) How can adjustment be both effective and predictable?
(ix) What type of regulatory target offers the best combination of efficient response to transient change in economic condition and solid achievement of long term environmental objectives?

Lesson 2: Adaptation Matters.

Natural, social, economic and political vulnerability to change cannot be evaluated in isolation. All systems interact, to be sure, but they also respond to change – a fact that is both a challenge and an opportunity. It is a challenge because modelers must look at dynamic portraits of change and envision how various systems might adjust to change, but it is also an opportunity because clear visions of how systems adapt will certainly provide insight into how policy and/or institutions might facilitate or hinder that adjustment. Careful consideration of adaptation can, moreover, support the creation of a typology of vulnerability. Some change *cum* adaptation will be inconsequential. Some will feel like an *accident* – uncomfortable for a short time, but correctable. Other change will be irreversible and uncomfortable over a longer period, but adaptation can be expected to mitigate against the *misery*. Some change might turn out to be catastrophic, though – irreversible and unavoidably damaging. Identifying how such *catastrophe* might occur is the first step to making certain that it does not happen.

Effective adaptation will, of course, be possible only if the relevant decision-makers are provided with useful, accurate and credible information on a timely basis. Providing that information given the enormous uncertainties that surround our understanding of climate change is a second challenge that the next generation of assessment models cannot ignore. Compound this uncertainty with the natural variability that will always cloud our view of what is actually happening, and creating mechanisms by which decision-makers receive useful information that they actually believe will be doubly challenging. Careful assessment of how to respond to climate change will, nonetheless, turn in large measure on how successful modelers can be in translating insight about the value of information into insight about how to best convey its content. Modelers will need to answers to questions like:

(i) How do people and institutions learn about changes in their environment?
(ii) Where do they turn for credible information?
(iii) How is credible information conveyed most effectively?
(iv) How do different people and institutions located in different political, economic, social, and cultural environments respond to change?
(v) What constraints do they face?

(vi) How do they manage risk?
(vii) Methodologically, how can identify sectors and/or regions where the answers to these questions will best inform either the policy community and/or the research community?

Lesson 3: Systems Adapt to Policies as Well as Environmental Change

This point can be taken to be nearly axiomatic, but it is frequently ignored if not forgotten. Indeed, many who call for ambitious near-term emissions reductions so that marginal communities can be spared the increased long-term pressure of climate change fail to see that the corresponding higher energy prices could easily create even larger stress over the very near-term. Many of the assessment efforts include elaborate sectoral models designed to track the market-based implications of a wide variety of policy options, though; and these implications are really adaptations. Their cost is not typically calibrated separately; but their dimension can be tracked by running alternative specifications of substitution possibilities, market rigidities, and so on. All of the questions listed in Lesson 2 therefore apply (and we may be further along in providing answers than we think in the response-to-policy area); but a few others must be added to the list:

(i) Are there natural, physical, social and/or economic sectors that might be more vulnerable to global change policy than they are to climate change, itself?
(ii) Are those vulnerabilities sensitive to the design of a mitigation policy, or are they more closely associated with the policy target?
(iii) How are these vulnerabilities distributed geographically, and is there any pattern to these distributions?
(iv) Are there ways of designing hybrid policies and/or policy-based adaptation so that the potential harm is diminished without intolerable undercutting of our ability to meet global objectives

Lesson 4: Uncertainty is Ubiquitous

Analyses of vulnerability to climate change should no longer concentrate so exclusively on middle-of-the-road scenarios of what the future might hold. There is a real danger that the very process of international scientific assessments of the sort orchestrated by the IPCC systematically discounts *possible but unlikely extreme events*; and so there is a real danger that the international process is leading the assessment community into a false sense of security. Evaluation of vulnerability to climate change should, as a result, expand its scope well beyond the inner-quartile range of accepted opinion. Researchers should look for critical climate and impact thresholds, where they exist; and perhaps they should strive to express vulnerability in terms of response functions that reflect those thresholds.

Even more important is the investigation of potentially catastrophic (i. e. irreversible, intolerable, and discontinuous) events of regional or global nature. Such extreme phenomena can no longer fall on the "cutting room floor" of the IPCC process. They must, instead, be given their due in a systematic way. Experts from all relevant disciplines should be asked:

(i) What might a collection of plausible (but not necessarily likely) stories of how the future might turn catastrophic look like?
(ii) Which of these stories is *not implausible?*
(iii) What natural or social feedbacks might automatically intervene disaster struck in stories that are implausible?
(iv) Is it possible to identify signposts, i. e. robust indicators, that would serve as harbingers of catastrophe and help to determine *safe guardrails* for climate policy designs?

On a slightly less dramatic scale of consequence but a higher scale of likelihood, both evolutionary and guardrail policy designers will focus much of their attention on critical thresholds. These may be defined in terms of the level and pace of climate change and their social, economic and/or political impacts of the level and pace of climate change policy; but

(v) Where are the critical thresholds in the climate system broadly defined?
(vi) How can they be described?
(vii) Are there any leading indicators that might serve as warnings that a threshold is near?

Lesson 5: There is a Continued Role for Dynamic Optimization.

Economics has a long tradition of studying perfectly competitive markets. Since the time of Adam Smith, their operation and efficiency properties have been a fascination, but not because their underlying assumptions are descriptive of a large portion of reality. Competitive markets are studied, instead, because of their efficiency properties. Competitive equilibria are "pareto efficient"; i. e., once equilibrium has been achieved, no single citizen can be made better-off without diminishing the welfare of someone else. Competitive markets may not distribute resources in "best" way possible (however that might be defined), but at least no resources are being wasted; and so it is impossible to "improve" the distributional properties of equilibrium by finding some unallocated surplus and "giving" it to somebody. Competitive equilibria therefore provide convenient benchmarks against which to judge the economic cost of creating various market distortions in the interest of funding the provision of some public good or the protection of life and property, allowing alternative market structures to exist for one reason or another (e. g., historical, political, etc…), or adopting other second-best policies designed to make progress against some non-efficiency criterion like equity, and so on. It is thought to be good and proper to understand fully how competitive markets would work if they were pervasive; but it is understood that it is more important to compare those operations with the results of systematic imperfections that may or may not be correctable individually and which certainly interact to either amplify or diminish their individual cost.

Solutions to the dynamic optimization problem in global change policy can serve the same role. They offer insight into what we could do if we knew everything and could solve all of the policy design and distributional issues; and so they can serve as benchmarks against which to judge the cost of not knowing everything and/or failing in our attempts to design the maximally efficient policy for whatever reason. Used in this way, a virtually limitless list of questions can be posed. Given what we know now and can expect to know later, for example:

(i) What would be the value of resolving (either partially or totally) our uncertainty about various components of the climate system, and where would improved understanding have the most value in reducing the expected cost of mitigation policy, in distributing the burden of climate change more equitably, and so on?
(ii) What are the efficiency losses associated with alternative mechanisms for distributing the costs of adapting to climate change and/or to climate change policy, and how sensitive are those losses to the likelihood of extreme events at the global and/or regional levels?
(iii) What are the efficiency properties of targeting mitigating policy at fixed or variable concentration targets, fixed or variable emissions targets, and so on?
(iv) How should the definition of policy targets accommodate the possibility of extreme events?
(v) What are the efficiency properties of various patterns of policy design over time, and how sensitive are those properties to the definition of policy objectives, the frequency of adjustment, the threat of extreme events, and so on?
(vi) How sensitive are the answers to these questions to the identification of various signposts and thresholds of climate change, and what is the comparative value of each in the context of natural variability?
(vii) And so on?

Lesson 1: Policy design matters

How do we foster and sustain coordinated and timely assessment of:

(i) the means and mechanisms by which climate policies can be adjusted?
(ii) the monitoring and dissemination of the information upon which those adjustments will be implemented?
(iii) the definition of their respective targets?

How are the costs and major benefits of climate change and various policy options distributed?

Upon what major state variables do those distributions depend?

How susceptible are those distributions to changes in the social, political, and economic condition of various nations and/or regions, especially if those changes are driven by non-environmental concerns?

What type of international regulatory mechanism can best handle the complication of an evolving global climate policy?

How can adjustment be both effective and predictable?

What type of regulatory target offers the best combination of efficient response to transient change in economic condition and solid achievement of long term environmental objectives?

Lesson 2: Adaptation matters

How do people and institutions learn about changes in their environment?

Where do they turn for credible information?

How is credible information conveyed most effectively?

How do different people and institutions located in different political, economic, social, and cultural environments respond to change?

What constraints do they face?

How do they manage risk?

Methodologically, how can identify sectors and/or regions where the answers to these questions will best inform either the policy community and/or the research community?

Lesson 3: Systems adapt to policies

Are there natural, physical, social and/or economic sectors that might be more vulnerable to global change policy than they are to climate change, itself?

Are those vulnerabilities sensitive to the design of the policy, or are they more closely associated with the policy target?

How are these vulnerabilities distributed geographically, and is there any pattern to these distributions?

Are there ways of designing hybrid policies and/or policy-based adaptation so that the potential harm is diminished without intolerable undercutting of our ability to meet global objectives?

Tab. 4
The next generation of questions

Lesson 4: Uncertainty is ubiquitous

What might a collection of plausible (but not necessarily likely) stories of how the future might turn catastrophic look like?

(i) Which of these stories is *not implausible?*
(ii) What natural or social feedbacks might automatically intervene disaster struck in stories that are implausible?
(iii) Is it possible to identify signposts, i. e. robust indicators, that would serve as harbingers of catastrophe and help to determine *safe guardrails* for climate policy designs?

Where are the critical natural, social, political, cultural, etc… thresholds in the climate system broadly defined?

How can they be described?

Are there any leading indicators that might serve as warnings that a threshold is near?

Lesson 5: A role for dynamic optimization

What would be the value of resolving (either partially or totally) our uncertainty about various components of the climate system, and where would improved understanding have the most value in reducing the expected cost of mitigation policy, in distributing the burden of climate change more equitably, and so on?

What are the efficiency losses associated with alternative mechanisms for distributing the costs of adapting to climate change and/or to climate change policy, and how sensitive are those losses to the likelihood of extreme events at the global and/or regional levels?

What are the efficiency properties of targeting mitigating policy at fixed or variable concentration targets, fixed or variable emissions targets, and so on?

How should the definition of policy targets accommodate the possibility of extreme events?

What are the efficiency properties of various patterns of policy design over time, and how sensitive are those properties to the definition of policy objectives, the frequency of adjustment, the threat of extreme events, and so on?

How sensitive are the answers to these questions to the identification of various signposts and thresholds of climate change, and what is the comparative value of each in the context of natural variability?

Tab. 4, continued
The next generation of questions

IV Some Concluding Comments

Section I began this discussion the gloomy observation that dynamic optimization in models that integrate across the entire climate system are hopelessly shorthanded in their battle to design appropriate and defensible mitigation policy. Section III closed with the suggestion that dynamic optimization still has a role to play: one of providing benchmarks against which to various response options *according to one design criteria – least cost economic efficiency.* There are other criteria, of course, and designing responses that more effectively achieve their embodied goals will cost more. Their identification is the point of the intervening discussion. But we return to the integrated, efficiency-based models to ask:

(i) How much more will meeting other objectives cost?
(ii) Is the global community willing to pay that much?
(iii) What are the associated opportunity costs?

And we end with one more: How can we design a global institution that can make these judgments and respond with appropriate policies that its global constituency will embrace? Climate change is perhaps the first truly global long-run problem that will require such an institution. Progress needs to be made in its design over the near-term when the stakes are still relatively low and manageable.

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