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Costing non-linearities, surprises, and irreversible events

Pacific and Asian Journal of Energy **10**(1): 81–106

Abstract The primary purpose of this paper is to highlight issues that are crucial when costing climatic impacts, particularly when the possibility is allowed for non-linearities, surprises, and irreversible events. The assumptions made when carrying out such exercises largely explain why different authors obtain different policy conclusions. Uncertainties become more significant when projections of climatic impacts are considered. There is uncertainty about how the biosphere will respond to human-induced climate change. However, it is clear that life, biogeochemical cycles, and climate are linked components of a highly interactive system. Non-linearities and the likelihood of rapid, unanticipated events (surprises) require that costing methods use a wide range of estimates for key parameters or structural formulations, and that, when possible, results be cast in probabilistic terms rather than central tendencies since the latter mask the policy-relevant wide range of potential results such a diversity of approaches implies. Costs need also to be presented in more numeraires than just monetary ones. This paper recommends that key for authors of scientific assessments is transparency of assumptions and the use of as wide a range of eventualities (and their attendant probabilities) as possible to help decision makers become aware of the arguments for flexibility of policy options.

Valuing climate change under uncertainty

The combination of increasing population and per capita energy consumption will contribute to increasing CO_2 (carbon dioxide) and sulphate emissions over the 21st century, but projections of the extent of their increase are uncertain. According to IPCC (Inter Governmental Panel on Climatic Change) (1996a), CO_2 concentration will double preindustrial levels by the middle of the 21st century, which is projected to lead to a warming of 1 °C to more than 5 °C by the end of the 21st century. Warming of 1 °C could have significant implications for species adaptation, whereas warming of 5 °C or more could have catastrophic effects on natural and human ecosystems, including serious coastal flooding. The overall annual cost of these impacts in 'market sectors' of the economy could run into tens of billions of dollars (Smith and Tirpak 1990, IPCC 1996b). Although fossil fuel use contributes substantially to such impacts, associated costs are rarely included in the price of conventional fuels; they are externalized. Internalizing these environmental externalities (Nordhaus 1992, IPCC 1996c, Goulder and Kennedy 1997) is a principal goal of international climate policy analyses.

Uncertainties become more significant when projections of climatic impacts are considered. The extent of the human imprints on the environment is unprecedented: human-induced climate change is projected to occur at a rapid rate, natural habitat is fragmented for agriculture, settlements, and other development activities, 'exotic' species are imported across natural biogeographic barriers, and the environment is assaulted by chemical agents (Root and Schneider 1993). It is, therefore, essential to understand not only how much climate change is likely, but also how to characterize and analyze the value of the ecosystem services that might be disrupted. There is uncertainty about how the biosphere will respond to human-induced climate change. However, it is clear that life, biogeochemical cycles, and climate are linked components of a highly interactive system.

The primary purpose of this paper is to highlight issues that are crucial when costing climatic impacts, particularly when the possibility is allowed for non-linearities, surprises, and irreversible events. The assumptions made when carrying out such exercises largely explain why different authors obtain different policy conclusions. The overall cost of climate change involves the costs of mitigation, adaptation, and the remaining damages. Uncertainty and the possibility of surprises surround each of these components and have a profound effect on them. In this paper, first, we discuss the conditions for non-linear events and surprises, followed by their importance for the costing of climate damages. Finally, we consider various response strategies, including adaptation and mitigation.

Imaginable conditions for surprise

Rate of forcing

The most comprehensive models of a complicated coupled system like an ESM (earth system model) are likely to have unanticipated results when forced to change rapidly by external disturbances like CO_2 and aerosols. Indeed, some of the transient coupled atmosphere–ocean models run out for hundreds of years exhibit dramatic change to the basic climate state—radical change in global ocean currents (Manabe and Stouffer 1993, Haywood, Stouffer, Wetherald, et al. 1997, Rahmstorf 1999). Stocker and Schmittner (1997) argue that rapid alterations to oceanic currents could be induced by faster forcing rates.

Thompson and Schneider (1982) used simplified transient models to investigate whether the time evolving patterns of climate change might depend on the rate at which CO_2 concentrations increase. For slowly increasing CO_2 build-up scenarios, the model predicts the standard outcome: the increase in temperature at the poles is more than that in the tropics. Any change in equator–pole temperature differences creates altered regional climates, since temperature differences influence large-scale atmospheric wind and ocean current patterns. However, for rapid increases in CO_2 concentrations, Thompson and Schneider found a reversal of the equator–pole temperature difference in the Southern Hemisphere over many decades during and after the rapid build-up of CO_2. This would imply unexpected climatic conditions during the century or so the climate adjusts toward its new equilibrium state. In other words, the faster and harder we push on nature, the greater the chances for surprise—some of which are likely to be damaging.

Clearly, rapid transients or non-linear events are likely to cause alterations to higher statistical moments of the climate (e.g. week-to-week variability, seasonal amplitudes, day-to-night temperature differences, etc.). Such rapid or unexpected events are likely to contradict the 'invariance of higher moments'. Thus, resultant environmental or societal impacts are likely to be different from those that would occur with smoother, slower changes. The long-term impact of climate change may not be predictable solely from a single steady state outcome, but may well depend on the characteristics of the transient path; the outcome may be path-dependent. Any exercise, which neglects surprises or assumes transitivity of the earth system (i.e., a path-independent response) is, therefore questionable, and should carry a warning to users of the fundamental assumptions implicit in the technique dependent on steady state results.

Assessment and reporting of uncertainties

Moss and Schneider (2000) and Moss (this volume) note that the term uncertainty can range in implication from a lack of absolute sureness to such vagueness as to preclude anything more than informed guesses or speculation. Uncertainty results from lack of information, or is caused by disagreement about what is known or even knowable. Some categories of uncertainty are amenable to quantification, while others cannot be sensibly expressed in terms of probabilities. Uncertainty is not unique to the domain of climate change research. However, in climate research, problems are compounded by additional characteristics. These include their global scale, long time lags between forcing and response, low frequency variability with characteristic times greater than the length of most instrumental records, and the impossibility of before-the-fact experimental controls. Moreover, because climate change and other complex, socio-technical policy issues are not just scientific topics but also matters of public debate, it is important to recognize that even good data and thoughtful analysis may be insufficient to dispel some aspects of uncertainty associated with the different standards of evidence and degrees of risk aversion/acceptance that individuals participating in this debate may hold.

Surprises

A surprise is an unanticipated outcome. However, the IPCC (Intergovernmental Panel on Climate Change) SAR (Second Assessment Report), defines surprises as rapid, non-linear responses of the climate system to anthropogenic forcing, and cites analogies to paleoclimatic abrupt events to demonstrate the plausibility of such a possibility. The SAR also gives specific examples of such non-linear behaviours that the authors could envision as plausible (e.g. reorganization of thermohaline circulation, rapid deglaciation, fast changes to the carbon cycle).

It would be better to define these as imaginable abrupt events. The Working Group I SAR concludes its Summary for Policymakers with the statement that non-linear systems when rapidly forced are particularly subject to unexpected behaviour (IPCC 1996a). Of course, the system would be less rapidly forced if decision makers chose, as a matter of policy, to slow down the rate at which human activities modify the atmosphere. To deal with such questions the policy community needs to understand both the potential for surprises and how difficult it is for IAMs (integrated assessment models) to credibly evaluate the probabilities of currently imaginable surprises let alone those not currently envisioned (Schneider, Turner, and Morehouse Garriga 1998).

Valuation of costs of climate damage

Costing of extreme event climate damages

Subjective probability assessments of potential climate change impacts provide a crude metric for assigning dollar values to certain aspects of ecosystem services. Costs associated with global change can be anticipated and a preliminary value placed on some of the ecosystem services that could be affected. Evaluation of the losses from extreme climatic events, such as floods, droughts, and hurricanes is one way to assess the costs of climate change (Alexander, Schneider, and Lagerquist 1997).

Cautious projections indicate that a warmer climate and human activities such as urbanization, deforestation, depletion of aquifers, contamination of ground water, and poor irrigation practices will increase both the frequency and intensity of catastrophic floods and droughts (IPCC 1996a). Humanity remains vulnerable to extreme weather events. For example, between 1965 and 1985 floods in the United States claimed 1767 lives and caused property damage of more than $1.7 billion dollars. Alexander, Schneider, and Lagerquist (1997) base their estimates on federal expenditures because information of private insurance losses and costs are unavailable. Ultimately, the effects of these floods are felt across a wide range of economic sectors, as can be seen with the overall cost evaluation of the Midwest flood of 1993 (Table 1).

In the 1993 Midwest flood, 9 states and 525 counties declared disasters. The estimated federal response and recovery costs included $4.2 billion in direct federal expenditures, $1.3 billion in payments from federal insurance programmes, and more than $621 million in federal loans to individuals, businesses, and communities. In the upper Mississippi Valley states of Minnesota, Nebraska, North Dakota, and South Dakota, as well as Wisconsin and northern Iowa, losses were primarily agricultural. In Illinois, central Iowa, and Missouri, major losses occurred in agriculture as a result of bottomland flooding, but urban areas also sustained damages. Numerous impacts of the flooding are still largely unknown, including cumulative effects of releases of hazardous material such as pesticides, herbicides, and other toxics; effects on groundwater hydrology and groundwater quality; distribution of contaminated river sediments; and alteration of forest canopy and sub-canopy structure. In addition, the loss of tax revenue has not been quantified for the Midwest flood. While not all costs of the flood can be directly calculated in monetary terms, both quantifiable and non-quantifiable costs were significant in magnitude and importance. This event, though not directly caused by anthropogenic climate change, allows a rough estimate of the magnitude of costs should such climate change cause increases in extreme weather events. Moreover, similar events in less developed parts of the world (e.g. flooding from Hurricane Mitch in Central America) may have caused less absolute monetary damages but greater losses in terms of human life, infrastructure and the social fabric of whole communities, not to mention the much higher percentage loss to GDP. Clearly, it is important to be explicit about the units of cost (numeraire) being considered in each specific case.

Like floods, severe droughts of the 20th century have affected both the biophysical and

Table 1 Summary of federal expenditures for the Midwest flood of 1993 (million US dollars)

	Missouri	Iowa	Minnesota	Illinois	Other states[a]	Total
USDA[b]	141.6	376.2	446.2	63.3	512.2	1,699.9
FEMA[c]	291.5	189.8	62.9	197.5	290.9	1,098.0
HUD[d]	152.1	107.7	29.8	94.9	75.1	500.0
Commerce	51.9	48.5	7.9	8.4	23.8	201.3
USACE[e]	128.7	9.7	0.3	70.3	12.0	253.1
HHS	19.3	22.8	4.0	7.4	15.2	75.0
Education	4.5	11.1	0.8	1.4	2.2	100.0
Labour	15.0	15.0	5.0	10.0	19.6	64.6
National Community	1.0	1.2	0.7	0.4	0.7	4.0
DOT[f]	73.5	22.1	7.3	33.3	36.9	146.7
EPA[g]	7.6	4.6	2.2	5.3	12.4	34.0
DOI[h]	5.1	2.1	6.0	11.8	8.3	41.2
Total	891.8	810.8	573.1	504.0	1,009.3	4,217.8

[a] Denotes combined costs, including those for the states of Kansas, Nebraska, North Dakota, South Dakota, and Wisconsin; [b] United States Department of Agriculture; [c] Federal Emergency Management Agency; [d] Housing and Urban Development; [e] United States Army Corps of Engineers; HHS, Department of Health and Human Services; [f] Department of Transportaiton; [g] Environmental Protection Agency; [h] Department of the Interior.
Source Interagency Floodplain Management Review Committee report to the Administrative Floodplain Management Review Committee report to the Administrative Floodplain Management Task Force, 1994.

socio-economic systems of many regions. Estimated damage from the 1988 drought in the Midwestern United States shows a reduction in agricultural output by approximately one-third, as well as billions of dollars in property damage.

Hurricanes can also cause devastation in tens of billions of dollars. Warmer surface waters in the oceans currently produce stronger hurricanes. Other meteorological factors are involved, though, that may act to increase or decrease the intensity of hurricanes with climate change.

Damage assessment is one way to relate the cost of inland and coastal flooding, droughts, and hurricanes to the value of preventing the disruption of climate stability. In the 1993 Midwest flood, for example, Alexander, Schneider, and Lagerquist (1997) delineate the costs of a single event. It is also possible to perform a more integrated analysis, such as the cost assessment of future sea level rise along the US coasts associated with possible ice cap melting or with ocean warming and the resulting thermal expansion of the waters. In a probability distribution of future sea level rise by 2100, changes range from slightly negative values to a metre or more rise, with the mid point of the distribution being approximately half a metre (Titus and Narayanan 1996). Many studies have assessed the potential economic costs of sea level rise along the developed coastline of the United States. For a 50-cm rise in sea level by 2100, estimates of potential costs range from $20.4 billion (Yohe, Neumann, Marshall, et al. 1996) to $138 billion (Yohe 1989) in lost property—depending on the levels of adaptation assumed. The following sections explore how the costs of prevention compare to the losses potentially sustained by increasing floods and droughts or by future sea level rises, by placing a value on climate changes and abatement.

Methods of valuation

Assessing the cost of climate requires estimates of both monetary and non-monetary impacts. While the former is difficult, the latter is even more complicated and controversial. The need for alternative methods of evaluation of these climate-related ecosystem services is clear when examining preliminary public opinion responses of global warming. In a controversial method called contingent valuation (Goulder and Kennedy 1997), respondents are surveyed to determine how much they would be willing to pay to prevent a given global climate change scenario or how much money they would require to permit a given amount of change. The difficulties with this type of valuing of environmental goods and processes are immense, especially since much of the evaluation is subjective. Public opinion depends, in part, on people's exposure and the level of education and information about these issues.

In a Southern California study, the contingent valuation technique was applied to determine the influence of potential changes in temperature and precipitation resulting from global warming on respondents' willingness to pay (Berk and Schulman 1995). Respondents were provided with a baseline microclimate for the region before future climate scenarios were evaluated. For example, for residents living in coastal communities, the baseline climate over the past ten years was described as having: (1) an average high temperature in summers of 75 °F, (2) daily high temperature range from 70–80 °F, with some days having over 90 °F, and (3) an average of twenty inches per year of rain. With these and other scenarios, predicted probabilities were determined from the respondents' willingness to pay for the abatement of different mean high temperatures. In these scenarios, respondents were willing to pay an average of $140 to offset a mean high temperature of 100 °F, while a mean high temperature of 80 °F was worth approximately $100. This represents a 40% increase in willingness to pay for a 20 °F rise in temperature and other scenario characteristics. The residents, however, reached a plateau in their willingness to pay at about 100 °F. They were not willing to pay much more to prevent 120 °F mean high temperatures than to prevent 110 °F mean high temperatures (Figure 1). This is dissimilar to the respondents in the Nordhaus (1994a) survey of experts who all assigned accelerating damage costs to climate change scenarios as the change became larger—a plausible assumption given that damages are often non-linearly larger the further changes are from current means.

However, the actual damages to the Los Angeles basin residents from mean high temperatures of 110 °F or more would be considerably more costly than those from 100 °F (e.g., given that landscaping costs alone are tens of thousands of dollars, $140 is a vast understatement). Berk and Schulman (1995) caution against taking the dollar values from the

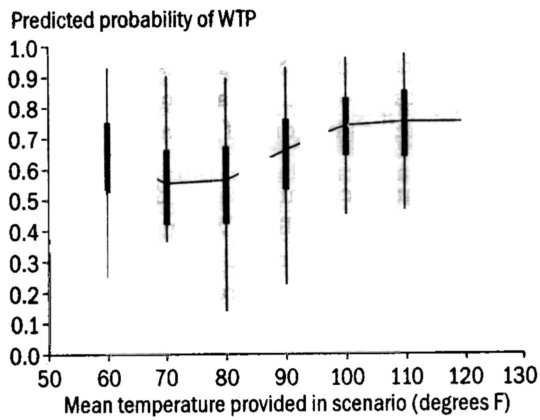


Figure 1 Predicted probabilities of Los Angeles survey respondents' willingness to pay for the abatement of different mean daily high temperatures
From Alexander et al. 1997. Source: Berk and Shulman 1995.

survey literally or using them in cost-benefit analyses, as they confound several sources of value including stewardship and altruism. In addition, some of the climate changes are well above the range of current scientific estimates of greenhouse warming (IPCC 1996a). The survey was not done in conjunction with atmospheric scientists and climatologists who could provide more realistic climate scenarios or ecologists, public health officials, or others who could help the respondents realize what such warming might mean for trees, birds, or people. This highlights the difficulty in finding acceptable methods to place values on the climatic components of ecosystem services. Therefore, contingent valuation points out that people are willing to pay to preserve ecosystem services, but require additional information to value, more realistically, climate and other environmental services.

Discounting

Discounting plays a crucial role in the economics of climate change. Changes in this parameter largely explain why authors such as Nordhaus (1994b) and Manne, Mendelsohn, and Richels (1995), find optimal emissions increasing by a factor of three or so over the next century whereas Cline (1992), Azar and Sterner (1996), Hasselmann, Hasselmann, Giering, et al. (1997), and Schultz and Kasting (1997) find that substantial reductions can be justified within the framework of cost-benefit analysis using damage functions similar to those of Nordhaus. The reason is that discount rates will eventually reduce future damage costs to negligible present values. Consider a climate impact that would cost one billion US dollars 200 years from now. A discount rate of 5% per year would make the present value of that future cost equal to

US $58 000, while a discount rate of 10% per year, would make the present value equal to US $5. There are two approaches to finding an appropriate discount rate: the descriptive and prescriptive approaches (Arrow, Cline, Maler, et al. 1996, Nordhaus 1997, Markandya 1999).

The descriptive approach focuses on observed market interest rates to ensure efficiency. For instance, if the market interest rate is 10% and there is a choice between a cost of US $100 today and US $109 next year, the latter is chosen since US $100 set aside today would generate US $110 next year and 'earn' US $1 net. Thus, basing the discount rate on the observed market interest rate can be seen as a way to guarantee that investments are made in the most profitable projects.

However, the longer the time horizon, the less likely is compensation along the lines sketched above (i.e. long-term real rates of growth have been closer to 1% per year, not 10%). This means that one would explicitly have to discuss trade-offs between consumption today and in the distant future, which is the focus of the second approach.

The prescriptive approach emphasizes that normative questions are involved in valuing the future. Proponents of this method often base the discount rate on the SRTP (social rate of time preference), which includes two main reasons for discounting—the expectation that we are going to get richer in the future in combination with decreasing marginal utility of consumption (i.e. we get less 'satisfaction' per additional unit of consumption), and impatience, which is often referred to as pure rate of time preference. In the prescriptive approach, the choice of discount rate entails a choice on how the future should be valued. This means that there is no objectively correct way to value the future, rather it is a question of value judgements.

When applying the prescriptive approach, a normative basis is sought for the pure rate of time preference. Proponents of intergenerational equity argue that the pure rate of time preference, but not necessarily the discount rate, should be zero, since it is difficult to find an argument why individual myopia should translate into giving lower weight to the welfare of future generations. Similar views have been expressed by Sidgwick (1890), Ramsey (1928), Harrod (1948), Rawls (1972), Spash and d'Arge (1989), Broome (1992), Cline (1992), Solow (1992), Price (1993), Eriksson (1994), Khanna and Chapman (1996), Azar and Sterner (1996), Rabl (1996), and Schultz and Kasting (1997).

There is empirical evidence to suggest that individuals exhibit 'hyperbolic discounting', i.e. higher (than market) discount rates are used in the short term and lower discount rates are applied over the long term (Ainslie 1991). This behaviour is consistent with a common finding that 'human response to a change in a stimulus is inversely proportional to the pre-existing stimulus' (Heal 1997, p. 339). Azar and Sterner (1996) assume that per capita income grows logistically over the next century, and since the discount rate is proportional to growth rates, declining discount rates are obtained.

When valuing catastrophic impacts, the value for the discount rate depends on the magnitude of the damage. In Ramsey-type optimal growth models, the discount rate on goods (in this case equal to the social rate of time preference) is given by

$$r = \gamma g + \rho$$

where r is the discount rate, γ is the relative growth rate in per capita consumption, γ is the negative of the elasticity of marginal utility of consumption ($\gamma > 0$), and ρ is the pure rate of time preference. In IAMs, generally, r is positive. However, if climate change is really severe, such that future income falls rather than grows, then the discount rate becomes negative, provided r is sufficiently low (Azar and Johansson 1996). The discount factor can be obtained by integrating (1) over time

$$V(t) = \exp\left(-\int_0 r\,dt'\right) = \frac{u'(c(t))}{u'(c_0)} \left[\frac{c_0}{c(t)}\right] \qquad (2$$

where c is per capita consumption, utility functions are of constant-relative-risk-aversion type, and the pure rate of time preference is equal to zero. If future consumption rates fall below present levels, e.g. as a result of a climate catastrophe, the future should be valued higher than the present.

Despite their limitations, these alternate discount methods demonstrate the importance of the structure of the discount function. All cost assessments need to explicitly explore their sensitivity to alternative discounting values and structures.

Need for probability distributions

Attempts to achieve more consistency in assessing and reporting on uncertainties are beginning to receive increasing attention. Some researchers express concern that it is difficult to even know how to assign a distribution of probabilities for outcomes or processes laced with different types of uncertainties. However, the scientific complexity of the climate change issue and the need for information that is useful for policy formulation requires researchers and policy makers to work together towards improved communication of uncertainties. The research community must also remember that users of IPCC reports often assume what they think the authors believed to be the distribution of probabilities it is not specified. Moss and Schneider (2000) argue (Moss, this volume) that it is more rational for experts to provide their best estimates of probability distributions and possible outliers than to have novice users make their own determinations.

In developing an estimate of a probability distribution, the first step is to document ranges and distributions in the literature, including sources of information on the key causes of uncertainty, describing how the ranges and distributions are constructed, and clearly specifying what they signify. This should include attention not only to the central tendency, but also to the end points of the range of outcomes, possible outliers, the likelihood that outcomes beyond the end points of the range might occur, and the type of distribution of potential outcomes (normal, bimodal, etc.).

The next step might be to quantitatively or qualitatively characterize the distribution of values that a parameter, variable, or outcome may take. The kind of range and confidence interval being constructed, or the types of possible outcomes included in the range should be clear. For example, do the end points (or outliers beyond them) include potential known or imaginable non-linear rapid events? Does the 'true' value fall into the specified range with a certain probability? Is the range defined to be one that includes two-thirds of modelled outcomes available in the literature?

Finally, an assessment of the central tendency of the distribution (if appropriate) should be provided. In developing a best estimate, authors need to guard against aggregation of results (spatial, temporal, or across scenarios) if it hides important regional or inter-temporal differences. Automatically different distributions should not be combined into one summary distribution.

Climate sensitivity is an example (Figure 2). Here scientists 2 and 4 offer a different estimate of range outliers (i.e. values below the 5th percentile or above the 95th percentile) for imaginable abrupt events. But the means and variance of scientists 2 and 4 are quite similar to most of the remaining scientists in this decision analytic survey, except scientist 5. This is an example where it would likely be inappropriate to aggregate all respondents' distributions into a single composite estimate of uncertainty since scientist 5 has a radically different mean and variance estimate than the other 15 scientists.

Truncating the probability distribution narrows the range of outcomes described and excludes outliers that may include 'surprises'. A truncated estimate of the full range of outcomes, does not convey to potential users a representation of the full range of uncertainty associated with the estimate. This has important implications regarding the extent to which the report accurately conveys uncertainties. Moss and Schneider (1999) acknowledge that some authors are likely to feel uncomfortable with the full range of uncertainty, because the likelihood of a 'surprise' or events at the tails of the distribution may be remote or essentially impossible to gauge, and the range implied could be large. Thus, there may be a case for providing a truncated range in addition to outliers for a specific case, provided that it is clearly explained what the provided range includes and/or excludes. If a truncated range is provided, the likelihood that the answer could lie outside the truncated distribution, should be specified along with the basis for specifying such possibilities.

Consider the example of using probability distributions to evaluate climate damages. Several studies suggest that climate change will have only minor economic impacts, and that an optimal policy would, therefore, incorporate only modest controls on greenhouse gas emissions (Kolstad 1993, Nordhaus 1992, Peck and Teisberg 1992). However, many of these 'modest controls' conclusions are based on point estimate values—results that are derived from a series of best guesses. This point estimate method fails to account for the wide range of plausible values for many parameters. Policy-making in the business, health, and security sectors is often based on hedging against low probability but high consequence outcomes. Thus, any climate policy analysis that represents best guess point values or limited (truncated) ranges of outcomes restricts the ability of policy makers to make strategic hedges against such risky outlier events.

Nordhaus (1992) has been criticized for considering only a single damage function and not accounting for abrupt climate 'surprise' scenarios. In response to such concerns, Nordhaus (1994a) conducted a survey of conventional economists, environmental economists, atmospheric scientists, and ecologists. Since these defy simple quantitative treatment, he took an alternative approach. Nordhaus used decision analytic techniques to sample the opinions of a wide range of experts who have looked at climatic impacts. He asked them to provide their subjective probabilities as to what they thought the costs to the world economy would be from several climate-warming scenarios. Their median estimates of the loss of GWP (gross world product) resulting from a 3 °C warming by 2090 varies between a loss of 0% and 21% of GWP with a mean of 1.9% (Nordhaus 1994a). Even a 2% loss of GWP in 1995, however, represents annual climate damage of hundreds of billions of dollars. For a 6 °C warming scenario, a median loss of 0.8%–62% with a mean of 5.5% was predicted.

This is an example of how estimates of probability distributions can inform. Although the numbers themselves are revealing, what is really interesting is the cultural divide across natural and social scientists in his study. The most striking difference in the study is that the social scientists (conventional economists predominantly), believe that even extreme climate change (i.e. 6 °C warming by 2090) would not impose severe economic losses. Although this scenario is usually considered to be a low probability event (Figure 2), it is equivalent to the magnitude of change from an ice age to an inter-glacial epoch in a hundred years, instead of thousands of years. Although with a wide range of uncertainty, most conventional economists surveyed still think climate change even this radical would, on average, have only a several per cent impact on the world economy in 2100. In their opinion, most natural services (Daily 1997) associated with current climate are either not likely to be significantly altered or could be substituted for with only modest harm to the economy.

On the other hand, natural scientists estimate the economic impact of extreme climate change twenty to thirty times higher than conventional economists (Nordhaus 1994a; Roughgarden and Schneider 1999). This group thinks the damages to the economy (including non-market components) from the severe climate change scenario would range from no less than several per cent lost up to 100%—the latter respondent assigned a 10% chance of the virtual destruction of civilization! The 50th percentile damage estimate from this group is an order of magnitude higher than that of the economists. Nordhaus suggests that the ones who know the most about the economy are less concerned while Schneider (1997a) suggests that the ones who know the most about the environment are more worried. The natural scientists, in essence, are less sanguine that human ingenuity could substitute for ecological services. Also, as Roughgarden and Schneider (1999) show, there is a positive correlation between the absolute amount of damage each respondent estimates and the percentage of total damages each assigns outside of standard national accounts (i.e. the natural scientists have higher percentages of their losses assigned to the non-market sectors). Regardless, either judgment involves both economic and ecological assessments, not single-disciplinary expertise. Clearly, the evolution of interdisciplinary communities cognizant of both economic and ecological knowledge and belief systems will be needed to make these subjective opinions more credible and to produce cost estimates that span a reasonable range of currently imaginable outcomes.

Note, however, that despite the magnitude in difference of damage estimates between economists and ecologists, the shape of the damage estimate curve was similar—the respondents indicated accelerating costs with higher climate changes. This stands in marked contrast to the flat willingness-to-pay curve in the contingent valuation example. The expert survey respondents, in general, are at least aware of non-linearities in climate change damages, unlike the lay public respondents.

The differences in various respondents' estimates of climate damages are cast into

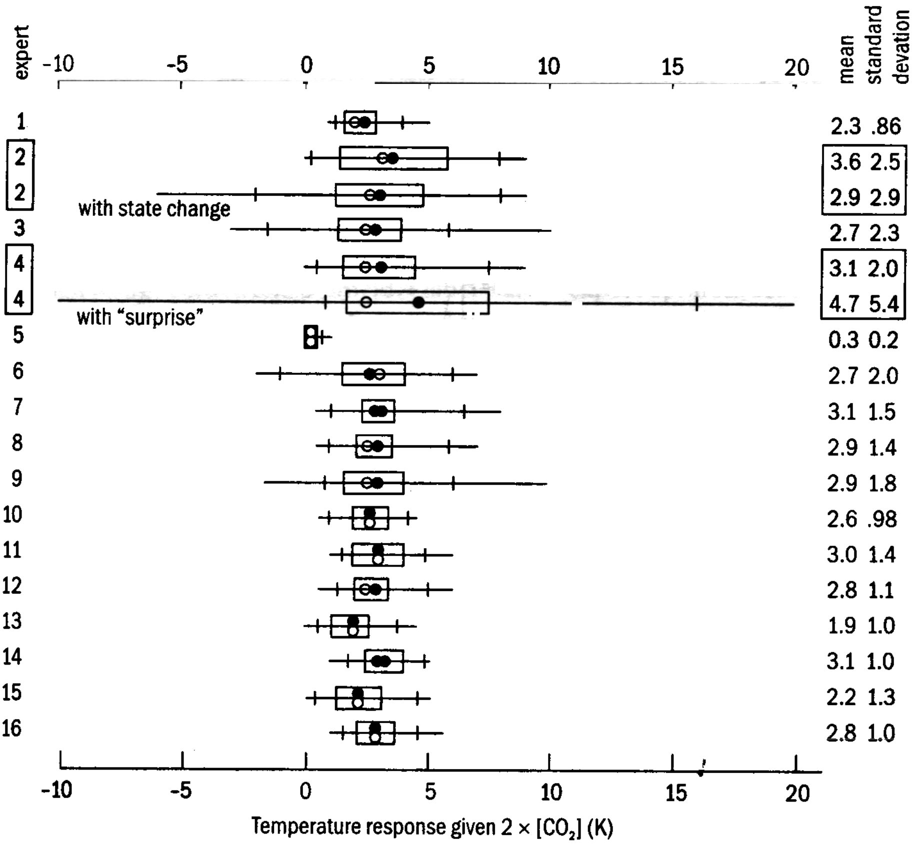


Figure 2 Box plots of elicited probability distributions of climate sensitivity, the change in globally averaged surface temperature for a doubling of CO_2 (2x[CO_2] forcing)
Note Horizontal line denotes range from minimum (1%) to maximum (99%) assessed possible values; vertical tick marks indicate locations of lower (5) and upper (95) percentiles; box indicates interval spanned by 50% confidence interval; solid dot is the mean and open dot is the median
Source Morgan and Keith (1995)

subjective probability distributions by Roughgarden and Schneider (1999) and then are used to recalculate the optimal carbon tax rate, using the Dynamic Integrated model of Climate and the Economy, DICE model, (Figure 3). The natural scientists' damage estimates processed by DICE model produce optimal carbon taxes several times higher than either the original Nordhaus estimate or those of his surveyed economists. Clearly, the use of probabilistic information, even if subjective, provides a much more representative picture of the broad views of the experts as well as a fairer representation of costs which, in turn, allow better potential policy insights from this IAM.

Several comparisons between the optimal carbon tax distributions from Roughgarden and Schneider (1999) and the original DICE model can be made, using the data summarized in Table 2 and Figure 3.

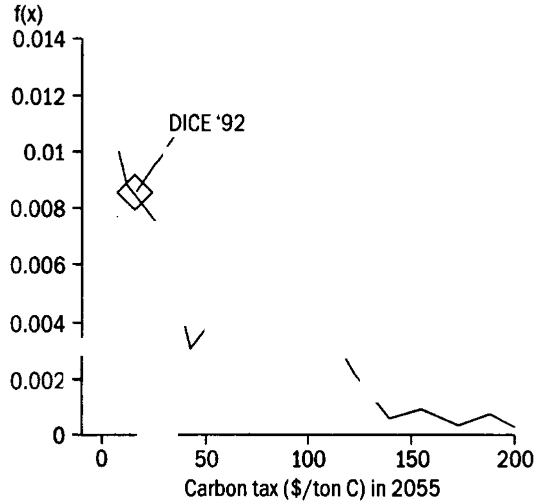
Comparison of the mode (the most frequent value) of the RS (Roughgarden and Schneider) distribution with the results of the original DICE model, indicates that DICE is a good representative of the expert opinion expressed in Nordhaus's survey. The modes of the optimal carbon tax distributions are slightly above zero, close to DICE's recommendation for a relatively light carbon tax. However, the other properties of the RS distributions justify different policies. The median and mean of the optimal carbon tax distributions range from three to eight times as high as those featured in the original DICE run.

The differences between the modes of the RS distributions and their medians and means

Table 2 Comparison of Monte Carlo simulation results with the standard DICE model

Source of	*Optimal*	*Carbon tax*	*($tonne C)*
Date	*1995*	*2055*	*2105*
DICE	5.24	15.04	21.73
Median	22.85	51.72	66.98
Mean	40.42	84.10	109.73
'Surprise'	193.29	383.39	517.09

Note Surprise values are 95th percentile results
Source Roughgarden and Schneider (1999)



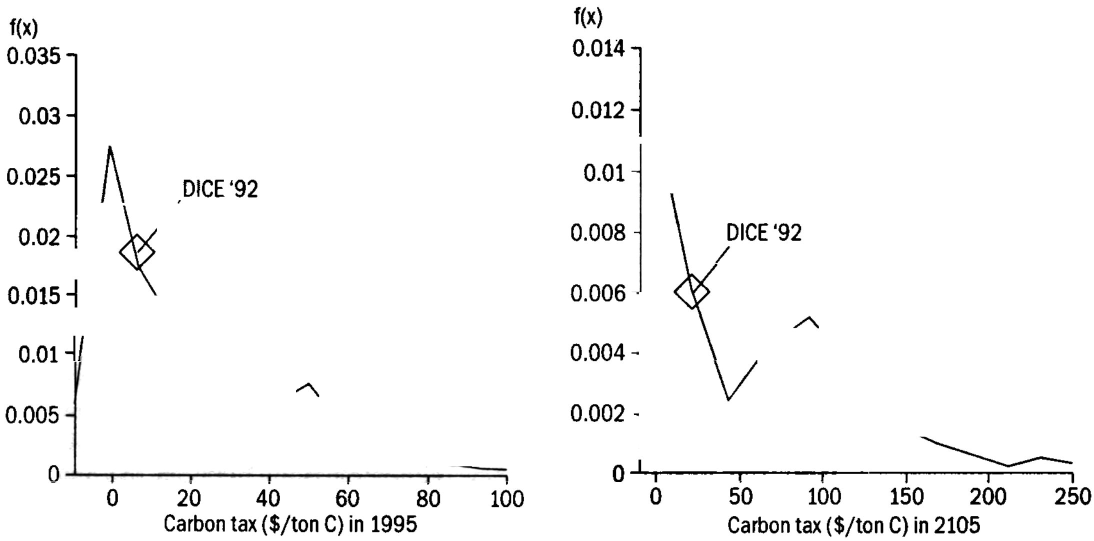


Figure 3 Probability distributions (f (x)) of optimal carbon taxes in the years 1995, 2055, and 2105 from Monte Carlo simulations
Note Points showing the optimal carbon taxes calculated by the DICE model are shown for comparison
Source Roughgarden and Schneider (1999)

can be attributed to the preponderance of right-skewness of the opinions given in Nordhaus's survey. Most respondents, economists and natural scientists alike, offer subjective probability distributions that were "right skewed". That is, most of the respondents consider the probability of severe climate damage ("nasty surprises") to be higher than the probability of "pleasant surprises". These long, heavy tails (which Roughgarden and Schneider label 'surprise' in Table 2) pull the medians and means of the distributions away from the modes. We take the 95th percentile results from the RS distributions as representative of these tails. The 'surprise' estimates for optimal carbon taxes in Table 2 are at least twenty times the level of those projected by DICE for the three years calculated (1995, 2055, and 2105).

Two different effects cause these differences. First, the means of these distributions (4.04% and 11.22% of the GWP damage for 3 °C warming and 6 °C warming, respectively) are much higher than the damage estimates used in DICE (1.33% and 5.32%). Thus, the simulation study of Roughgarden and Schneider uses more pessimistic damage functions than that of the original DICE model. Second, the non-linearities of the model will, on average, push optimal carbon taxes even higher. Intuitively, damage functions derived from these damage distributions will never give far more optimistic results than those with the original DICE damage function, but they will occasionally result in far more pessimistic outcomes. These occasional 'catastrophic' damage functions will lead to a relatively pessimistic expected value of output. In other words, the significant chance of a 'surprise' causes a much higher level of 'optimal' abatement, relative to the original DICE formulation.

In addition, Roughgarden and Schneider analyse the effects of the relative severity of the average survey damage estimate versus those of the non-linearities of the DICE model in a probabilistic analysis. Approximately one-third of the difference between the optimal carbon taxes of DICE and the means of their optimal carbon tax distributions are accounted for by the relatively high survey damage estimates, and the remaining two-thirds of the difference can be attributed to the non-linearities in the model.

In a sense, the original DICE carbon tax may be regarded as a point estimate between the mode and median of the distribution of expert opinion. However, output from a single model run does not display all the information available nor does it offer sufficient information to provide the insights needed for well-informed policy decisions. One cannot simply look at a recommendation for a 'five dollars per tonne carbon tax' and claim that higher carbon taxes are 'necessarily less economically efficient'. In particular, strategic hedging policies to deal with the 95th percentile, high damage outcome may well be chosen by policy makers, just as individuals or firms purchase insurance against low probability catastrophic outcomes. Regardless of how risk-prone or risk-averse is the individual decision maker, the characterization and range of uncertainties of the information provided by decision analysis tools must be made explicit and transparent to policy makers (Moss and Schneider 1997). This range of uncertainty should also include estimates for the subjective probability of varying climatic effects (Morgan and Keith 1995, Nordhaus 1994a), damage estimates, discount rates (Cline 1992, Chapman, Suri, and Hall 1995, Azar and Sterner 1996), carbon cycle effects on CO_2 uptake (Kaufmann 1997, Schultz and Kasting 1997), and the sensitivity of the economy to structural changes such as induced technological change (Grubb, Ha-Duong, and Chapuis 1974, Repetto and Austin 1997, Goulder and Schneider 1999, Azar and Dowlatabadi 1999). The end result of any set of integrated assessment modelling exercises will be, as always, the subjective choice of a decision maker (Schneider 1997b), but a more comprehensive analysis with uncertainties in all major components explicitly categorized and displayed will hopefully lead to a better-informed choice.

It is clear from the Nordhaus studies that knowledgeable experts from a variety of fields admit to a wide range of plausible outcomes – including both mild benefits and catastrophic losses – in the area of global environmental change. This condition is prone to misinterpretation by those unfamiliar with the wide range of probabilities most scientists attach to aspects of global climate change. In an interdisciplinary enterprise like the costing of climatic impacts or mitigation policies to be used as inputs to integrated assessment of global climate change problems, it is necessary to consider a wide range of possible outcomes, along with a representative sample of the subjective probabilities that assessment groups like the IPCC believe accompany each of those possible outcomes.

Which of the scientists, natural or social, Nordhaus interviewed are closer to the truth may one day be empirically determinable, but for the next decade or so, at least, the differences will remain paradigmatic. However, one policy-relevant certainty is that the optimal carbon tax calculated using damage estimates from the surveyed natural scientists is dramatically larger than the tax calculated using damage estimates from the surveyed social scientists (Roughgarden and Schneider 1999).

Distributional impacts

How should we value catastrophic impacts, such as the destruction of entire economies with tens of thousands losing their lives, the orphanage of children, and the collapse of civil institutions and normal civil life? Under such circumstances, conventional valuation methods become increasingly difficult to use and they even break down at some point. The impact of Hurricane Mitch on Honduras and Nicaragua provides one example of how climate-related events may have severe consequences on local economies and how difficult it is to value such impacts in monetary terms.

One reason why monetary evaluation becomes controversial is that the results depend on the level of income of those affected. For instance, the VOSL (value of a statistical live) is, according to conventional valuation methods, based on the willingness to pay for increased safety. Fankhauser (1995) estimated the VOSL at US $1 500 000 and US $100 000 in developed and poor developing countries, respectively. Thus, the social cost of the death of 15 000 people in Honduras becomes equal to the social cost of the death of 1000 people in the Netherlands. This example shows that the measure of social cost does not appropriately reflect the seriousness of an impact.

Alternatively, as a consequence of the standard assumption about declining marginal utility with respect to income, a loss of US $1 to a poor person is worth more than that to a rich person. This may provide a rational for introducing weight factors to give higher weight to costs that affect poor countries. Climate costing studies where this approach has been taken include Ayres and Walters (1991), Azar and Sterner (1996), Fankhauser, Tol, and Pearce (1997), Azar (1999), and Johansson-Stenman (1999). It may be shown that the additional weight given to losses in poor countries may compensate for the lower value attached to losses of human lives, so that equal weighted VOSL across countries is obtained.

However, let us put these difficulties aside and assume that these valuation methods are uncontroversial. Assume also, just as an example, that climate change would cause damage in Bangladesh equal to 80% of its GDP (gross domestic product), or roughly 0.1% of global GDP. If the global economy were growing at 2% per year, this assumed impact on Bangladesh would show up as merely a delay in global income by less than 3 weeks. In political terms, however, such an event would be considered more severe than a three-week delay in global income growth. This leads us to the question whether we have the right to trade costs of emission reduction in countries (e.g.

more efficient end-use energy technologies) with large-scale losses of lives and human health. Thus, in most conventional cost-benefit analyses, the concept of social costs is blind to distributional issues, which is one of the core issues in the climate change debate (Munasinghe 1999). This points to the necessity of using several numeraires, only one of which may be monetary terms, when presenting the costs of climate change.

Finally, it should also be noted that distributional issues are important not only when assessing impacts. The distribution of income is also a major determinant of the efficient solution. It is often said that distributional issues can be separated from questions of efficiency. The task for economists has then been to find the efficient solution, and then let policy makers take care of distributional impacts. However, the assumption that equity and efficiency can be separated only holds under the assumption that small (marginal) distributional changes are considered. Consider the construction of a huge dam, which is expected to yield social benefits of a billion US dollars at the expense of forced migration of one million peasants. Assume also that the WTP against the project of the peasants would only be US $100 per capita. Thus, the project would be 'more efficient'. However, if the farmers were richer, then they might have been able to express a WTP at US $1500 per capita, which would have made the dam construction economically inefficient considering 'full social costs'.

This illustrates how the distribution of income affects what is considered efficient. It is simply because the farmers are poor, that it becomes efficient to carry out a project that might have severe negative impacts on their livelihood. This stands in contrast with the policy position against dam construction on the grounds that it is the poor and vulnerable who can be expected to suffer for its construction (e.g. the projects along the Narmada river in India or the Yangtze river in China). The example shows that the importance of a person's opinion depends on his/her ability to pay for it. This may (or may not) be acceptable for day-to-day transactions over goods and services, but it is at best politically contentious when the transactions involve the livelihood and fates the multitudes. Furthermore, this method, which could be labelled 'one dollar one vote', clashes with the principles of democracy (one person, one vote), especially when crucial, path forming societal decisions are being taken.

Five numeraires: monetary loss, loss of life, quality of life (including coercion to migrate, conflict over resources, cultural diversity, loss of cultural heritage sites, etc.), species or biodiversity loss, and distribution/equity

Any comprehensive attempt to evaluate the societal value of climate change should include such things as loss of species diversity, loss of coastline from rising sea level, environmental displacement of persons, change in income distributions, and agricultural losses. The environment also possesses intrinsic worth without a specified market value, such as its aesthetic appeal, which suggests that the environment should be treated as an independent variable in utility. This is what is meant by 'existence value'—a priority is placed on preserving the environment, even if it is not intended to be personally experienced. This is in addition to the 'option value' of the environment, which we may want to preserve for our possible personal use in the future. There is little agreement on how to place a dollar value on the non-market impacts of climate change, such as the loss of human life, biodiversity, or ecosystem services.

Addressing this, Nordhaus (1994a) asked his expert panel to separate their subjective probability estimates of climate damages into market (standard national accounts) and non-market damages, such as the value of lost species, value of lost wetlands from sea level rise, or the costs from conflicts that might be induced by the creation of "environmental refugees" (Myers 1993) or any of the other non-market amenities. Economists and natural scientists assigned different fractions of damages to the non-market sector, which parallels the difference in degree of concern over climate change. Roughgarden and Schneider (1999) find that most respondents who had estimated large damages placed the bulk of them in the non-market category (natural scientists), and those with low estimates had assigned low damages to non-market values (economists). This raises a major issue about the dimensions of damages, which need even finer subdivision than the market and non-market binary characterization.

It is essential for analysis of costs of climate change impacts or mitigation strategies to consider explicitly alternative numeraires and to be as clear as possible which is being used and which omitted. Moreover, before any aggregation is attempted (e.g. cost-benefit optimization strategies), authors should first disaggregate costs and benefits into several numeraires and then provide a 'traceable account' (Moss and Schneider 2000) of how they were re-aggregated. Such transparency is essential given the normative nature of valuation of various consequences characterized by the five numeraires.

Rapid changes and adaptability

Natural variability masks trends and delays adaptation

The assumptions underlying climate change scenarios determine to a large degree, the impacts that specific climatic change scenarios are predicted to have on agriculture, coastlines or forestry. For example, some analysts (Mendelsohn, Nordhaus, and Shaw 1996; Mendelsohn, Morrison, Schlesinger et al. 2000) employ "hedonic methods" by using cross sectional measure as a proxy to estimate adaptation responses to climate change over time. However, such static analytic methods neglect transient dynamics, irreversibilities and higher moments like changes in seasonality and variability (see Schneider 1997b for a criticism of the use of "ergodic economics" to model climate change over time). One of the major differences in estimates of climatic impacts across different studies is how the IAM treats the adaptation of the sector under study. For example, it has often been assumed that agriculture is the most vulnerable economic market sector to climate change. For decades agronomists have calculated potential changes in crop yields from various climate change scenarios, suggesting some regions now too hot would sustain heavy losses from warming whereas others, now too cold, could gain (Rosenzweig, Parry, and Fischer 1994, Smith and Tirpak 1990). But N Rosenberg (Rosenberg and Scott 1994) has long argued that such agricultural impact studies implicitly invoke the 'dumb farmer assumption'. That is, they neglect the fact that farmers do adapt to changing market, technology, and climatic conditions. Agricultural economists like John Reilly (Reilly, Baethgen, Chege et al. 1996) argue that such adaptations will dramatically reduce the climate impact costs to market sectors like farming, transportation, coastal protection, energy use. Ecologists and social scientists, however, often dispute this optimism, since it neglects such real world problems as people's resistance to trying unfamiliar practices, problems with new technologies, unexpected pest outbreaks (Ehrlich, Ehrlich, and Daily 1995), or the high degree of natural variability of weather. The latter is likely to mask the slowly evolving human-induced climatic signal and discourage farmers from risking anticipatory adaptation strategies based on climate model projections.

Clairvoyant adaptation is challenged by the noisy nature of the climatic system. It is doubtful that those in agriculture or situated along the coast will invest heavily in order to adapt their practices so as to pre-empt before-the-fact climate model projections, rather than react to actual events. One can only speculate on whether or not agricultural support institutions, the research establishment particularly, will be influenced by such projections. The high natural variability of climate is likely to mask any slowly evolving anthropogenically induced trends—real or forecasted. Therefore, adaptations to slowly evolving trends embedded in a noisy background of inherent variability are likely to be delayed by decades behind the slowly evolving global change trends (Kaiser, Riha, Wilks, et al. 1993, Schneider 1996, Morgan and Dowlatabadi 1996, Kolstad, Kelly, and Mitchell 1999). Moreover, were agents to mistake background variability for trend or vice versa, the possibility arises of adaptation following the wrong set of climatic cues, and setting up a major system malfunction. In particular, agents might be more influenced by regional anomalies of the recent past in projecting future trends. They may be unaware of the likelihood that recent anomalous experience in one region may well be largely uncorrelated with slowly building long-term trends at a global scale or may be part of a transient response that will reverse later on. In addition, unwarranted complacency may result from the inability to foresee non-linear events.

It is doubtful that millions of disaggregated decision makers (farmers in this example) will respond uniformly or quickly to forecasts of global climatic changes from IAMs. On the other hand, one of the technological adaptations that could mitigate climatic impacts on agriculture is seed development to cope with altered climates. But, there are only a small number of seed companies capable of altering the genetic character of crops and marketing these better-adapted strains on a large scale to farmers (in OECD [Organisation of Economic Co-operation and Development]-like countries at least). Rather than millions of disaggregated decision makers at the farm level, therefore, there may be three or four orders of magnitude smaller numbers of decision makers. In essence, the problem in modelling adaptation rests on how to incorporate human behaviour via a set of decision rules into the structure of models so as to make them more 'actor-oriented'. Decision makers who turn to such later generations of IAMs to help inform them about the costs of climate change must be aware of the controversial nature of assumptions about adaptation behaviour of various actors, which often lurk invisibly in different impact assessment studies.

The case of coastal flooding is a good example of how incorporating climatic variability can significantly reduce the damage reduction potential adaptive activities might otherwise have offered if high levels of natural variability did not plague climate change trends. West and Dowlatabadi (2000) devised a set of decision rules by which coastal dwellers would chose to rebuild, remain in place, or abandon coastal structures, based on the random occurrence of storm surges superimposed on a slowly rising sea level trend. The 'noise' of such random storm surge events substantially alters the adaptability behaviour of coastal dwellers relative to those clairvoyant agents whose decision rules do not include the masking effects of climatic variability.

Passive versus anticipatory adaptation

Schneider and Thompson (1985), in an intercomparison of climate change, ozone depletion, and acid rain problems, differentiate passive adaptation (e.g. buying more water rights to offset impacts of a drying climate) from anticipatory adaptation. They suggest, as a hedging strategy, investing in a vigorous research and development programme for low-carbon energy systems in anticipation of the possibility of needing to reduce CO_2 emissions in the decades ahead. The idea is that it would be cheaper to switch to systems that were better developed as a result of such anticipatory investments made in advance. Such active (anticipatory) forms of adaptation (e.g. building a dam a few metres higher in anticipation of an altered future climate) have been prominent in most subsequent formal assessments of anthropogenic climate change (National Academy of Sciences 1991). Nearly all modern integrated assessments explicitly (Rosenberg 1993, Rosenzweig, Parry, and Fischer 1994, Reilly, Baethgen, Chege, et al. 1996), or implicitly (Mendelsohn, Nordhaus, and Shaw 1996, Mendelson, Morrison, Schlesinger, et al. 2000) attempt to incorporate (mostly passive) adaptation. While these studies should be applauded for attempting to recognize and quantitatively evaluate the implications of adaptive responses on the impact costs of climate change scenarios, serious problems with data, theory, and method remain. A wide range of assumptions should be part of any attempted quantification of adaptation (Carter, Parry, Harasawa, et al. 1994). Moreover, as repeatedly argued, both costs and benefits of climate change scenarios treated by any integrated assessment activity should be presented in the form of statistical distributions based on a wide range of subjective probability estimates of each step in the assessment process (Yohe 1991, Morgan and Dowlatabadi 1996, or Schneider 1997b).

Mitigation strategies and (optimal) carbon taxes

Decision makers face in strategic choices the climate change debate. If we do not slow down initially, it may be more costly or more difficult, to slow down fast enough if the risk of a catastrophic event materializes. Suppose, for instance, only minimal CO_2-abatement policies are put in place over the next decade or two. If it suddenly turns out that climate change is or can be expected to be much more severe than initially estimated, it will be more costly, or perhaps even impossible to meet certain targets.

Although we do not know which target is warranted, one popular strategy is to create flexibility – in timing and instruments – today so that as many options as possible remain open. Toth (see this volume) presents a range of alternative decision frameworks. These issues were central in the debate about timing of emission abatement.

The timing of emission reductions

To meet the ultimate goal of the United Nations Framework Convention on Climate Change, Wigley, Richels, and Edmonds (1996) claimed that it is cost-efficient to defer emission reductions a couple of decades, since this would give time to develop carbon-free technologies and to avoid a premature phase-out of the existing capital stock. Their position was challenged on several grounds (Austin 1997, Grubb 1997, Ha-Duong, Grubb, and Hourcade 1997, Schneider and Goulder 1997, Azar 1998, Azar and Dowlatabadi 1999). For instance, Yohe and Wallace (1996) and Ha-Duong, Grubb, and Hourcade (1997) used stochastic optimization techniques to determine the optimal hedging strategy under short-term uncertainty about which climate target to meet. Uncertainty was assumed to be resolved by 2020. Ha-Duong, Grubb, and Hourcade (1997) suggested that short-term abatement is justifiable on economic grounds, whereas Yohe and Wallace were less convinced. The main reason for their diverging results is that Ha-Duong, Grubb and Hourcade considered a symmetric probability distribution around 550 ppm, with a 2.5% probability that even a 400 ppm target had to be met, whereas Yohe and Wallace chose an uncertainty range as high as 550–800 ppm.

Thus, one may conclude that once we want to keep low stabilization targets within reach, it is 'optimal' to have substantial short-term emissions. One main driving factor for this result is that it will be costly to opt for higher atmospheric stabilization targets and then change the energy system at a fast rate if severe climatic trends unveil themselves. Unfortunately, the full effect of this is not seen in the study by Ha-Duong, Grubb, and Hourcade (1997) since they assume that the 400 ppm target may not even temporarily be overshot. This means that the model has to start abating in order to avoid that from happening, regardless of the probability that this target eventually has to be met.

The 'cost' of a carbon tax

Schneider and Goulder (1997) have developed an economic simulation model for the US, which takes into account incentives to invest in research and development, knowledge spillovers, and the functioning of R&D markets, to estimate the costs of reducing cumulative CO_2 emissions by 15% in the 100 years after 1995. By allowing energy R&D to compete with other economic sectors in a highly aggregated general equilibrium model of the US economy, Goulder and Schneider (1999) postulate that a noticeable carbon tax is likely to dramatically redistribute energy R&D investments from conventional to non-conventional sectors, thereby producing ITCs (induced technological changes) that lower long-term abatement costs. They also demonstrate that there may be an opportunity cost from ITC. The key variable in determining the opportunity cost is the fundability of human resources. If all knowledge generating labour is fully employed, then increased R&D in non-carbon technologies will necessarily come at a cost to reduced labour in conventional activities. Unfortunately, most integrated assessment models to date do not include any endogenous ITC formulation (or if they do, it is included in an ad hoc manner). Thus insights about the costs or timing of abatement policies derived from IAMs should be viewed as tentative.

Goulder and Schneider (1999) consider the GDP losses from a carbon tax introduced in 1995 and maintained at a constant rate of 25 dollars per tonne (1995 rate). The gross costs (i.e. the costs before accounting for environment-related benefits of abated CO_2) of a specified carbon tax are higher with ITC than without ITC because of the explicit inclusion of the opportunity costs of R&D. However, this comparison assumes no prior subsidies for R&D in any industry, no knowledge spillovers, and that all prior inefficiencies in R&D markets are absent. In general, these efficiency or optimality assumptions are not met in the economy. R&D market failures can be corrected by public sector investments like R&D subsidies to correct the market failure (Schneider and Goulder 1997). Finally, if there were serious prior inefficiencies in R&D markets such that the marginal benefit of R&D is much higher in alternative energy sectors than in conventional, carbon-based sectors or there were 'no regrets' energy system inefficiencies, then ITC can imply lower gross costs than would occur in its absence. There is a critical need to formally acknowledge the wide range of plausible cost estimates that arise when parameter value uncertainties are combined with structural assumptions and normative choices implicit in various numeraires.

Perspective on the costs of meeting the climate target

There is a widespread concern that CO_2 control will impose catastrophic economic costs. Nordhaus (1990) warns 'that a vague premonition of some potential disaster is, however, insufficient grounds to plunge the world into depression'. Nordhaus and other top-down modellers often find the costs of meeting stringent CO_2 control targets in trillions of dollars. Manne and Richels (1997), for example, estimate the global present value costs (using a 5% per year discount rate) of meeting a 450-ppm target to be as high as 4–14 trillion US dollars. Other top-down modellers report similar cost estimates. In absolute terms, this is a considerable cost and thus may create the impression that we cannot afford to reduce CO_2 emissions.

However, a different picture emerges from another perspective. This cost only has a minor impact on the overall growth rates and income levels in the economy in the models used to estimate it. In a survey of top-down studies, global per capita income by 2100 is assumed to be 5.4 times higher than at present if no carbon abatement occurs. If carbon emissions are kept at two-thirds of the present level for the 21st century, per capita income would be 5.1 times higher (Azar 1996). Given assumed growth rates, the global income would be delayed a couple of years before the higher income level is attained. Schneider (1993b), Grubb, Edmonds, ten Brink et al. (1993), and Anderson and Bird (1992) report similar observations. There is near consensus, even among top-down modellers, regarding this. Note that the full range of potential environmental benefits from reducing the emissions have not been included in these estimates (e.g. as Roughgarden and Schneider [1999] showed, a wide distribution of damage costs produces a very wide distribution of optimal carbon taxes).

The salience of the information provided by these modelling exercises to policy makers depends on the political context. The threat of climate change is increasingly being recognized as one of the most important challenges for the 21st century. There is mounting pressure from scientists and many different stakeholder groups to take action to reduce emissions, but the speed of action is still fairly low. Some politicians and representatives from certain business sectors continue to oppose measures to reduce CO_2 emissions. Perhaps, even more importantly, there is a genuine public concern that emission reduction might reduce the material standard of living (in absolute terms), force people into unemployment, or in the words of President Bush during the UNCED (United Nations Conference on Environment and Development) meeting in Rio de Janeiro in 1992, 'threaten the American way of life'.

Thus, although actual numbers are uncertain, top-down models clearly find that stringent CO_2 constraints are compatible with a significantly increased material standard of living and they do not threaten to plunge the world into depression. This way of presenting modelling results (i.e. showing that the relative paths of per capita GDP or consumption over the 21st century with and without carbon policies are almost identical) deserves more attention since there is a widespread impression amongst policy makers and the general public that the opposite holds true.

Conclusions

Non-linearities and the likelihood of rapid, unanticipated events (surprises) require that costing methods use a wide range of estimates for key parameters or structural formulations, and that, when possible, results be cast in probabilistic terms rather than central tendencies since the latter mask the policy-relevant wide range of potential results such a diversity of approaches implies. Costs need also to be presented in more numeraires than just monetary ones. Because monetary cost estimates may more conceal than highlight the ethical and moral dimensions of the potential climatic impacts, in particular impacts on human health, distribution of costs, or ecosystems. The underlying structural assumptions and parameter ranges should be explicitly given in costing analyses, to make the conclusions as transparent as possible. For example, while it is often acknowledged that a wide range of uncertainty accompanies estimates of climate damages from scenarios of anthropogenic climatic change (owing to uncertainties in adaptation capacity, synergistic impacts, etc.), it is less common (Moss and Schneider 1997) to have a comparably wide set of estimates for mitigation costs of carbon policies (e.g. a carbon tax being a common analytic benchmark). Yet, the tighter range of mitigation cost estimates occurs in part because standard costing methods make common assumptions about the lack of pre-existing market failures or do not explicitly account for the possibility of climate policy-induced technological changes reducing mitigation cost estimates (Repetto and Austin 1997, Grubb, Ha-Duong, and Chapuis 1994, Azar 1996, Goulder and Schneider 1999). Although such endogenous growth formulations are controversial, cost estimates made in their absence need to be labelled as not remotely covering the full range of plausible values to prevent policy makers from misunderstanding the limited scope of the more conventional results.

Moreover, in view of the wide range of plausible climatic change scenarios available in the literature – including a growing number of rapid non-linear change projections – it is important for costing analyses to consider many such scenarios, including the implications of rapid changes in emissions triggering non-linear climatic changes with potentially significant implications for costing.

In short, the key for authors of scientific assessments is transparency of assumptions and the use of as wide a range of eventualities (and their attendant probabilities) as possible to help decision makers become aware of the arguments for flexibility of policy options.

Acknowledgements

Stephen H Schneider and Kristin Kuntz-Duriseti acknowledge partial support from The Pew Charitable Trusts (through the Pew Center on Global Climate Change) and The Winslow Foundation, Washington, D C. Christian Azar acknowledges financial support from the Swedish Council for Planning and Coordination of Research (Stockholm).

Table 3 Percentage differences between corn yields simulated with baseline observed climate (1984–93) and corn yields simulated with 1/3, 2/3, and 3/3 of $2xCO_2$ climate change for three levels of adaptation: (1) no adaptation ('dumb farmer'), (2) perfect adaptation ('clairvoyant farmer'), and (3) adapatation lagged 20 years behind climate changes ('realistic farmer')

A *Central Iowa*

Climate Change (Reg CM)	*No Adaptation* (%)	*Perfect Adaptation* (%)	*Lagged Adaptation* (%)
1/3 of 2XCO2	–3	2	–3
2/3 of 2XCO2	–8	2	2
3/3 of 2XCO2	–17	–0.3	–3
Mean of Thirds	–10	1	–1

B *South Central Minnesota*

Climate Change (Reg CM)	*No Adaptation* (%)	*Perfect Adaptation* (%)	*Lagged Adaptation* (%)
1/3 of 2XCO2	8	13	8
2/3 of 2XCO2	12	23	17
3/3 of 2XCO2	10	24	22
Mean of Thirds	10	20	16

Source Schneider, Easterling, and Mearns (2000)

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