

## **Inside the Integrated Assessment Models: Four Issues in Climate Economics**

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### **Abstract**

Good climate policy requires the best possible understanding of how climatic change will impact on human lives and livelihoods in both industrialized and developing countries. Our review of recent contributions to the climate-economics literature assesses 30 existing integrated assessment models in terms of four key aspects of the nexus of climate and the economy: the connection between the model structure and the type of results produced; uncertainty in climate outcomes and the projection of future damages; equity across time and space; and abatement costs and the endogeneity of technological change. Differences in treatment of these issues are substantial, and directly affect model results and their implied policy prescriptions. Much can be learned about climate economics and modeling technique from the best practices in these areas; there is unfortunately no existing model that incorporates the best practices on all or most of the questions we examine.

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## I. Introduction

There is no shortage of models that join climate to economy with the goal of predicting the impacts of greenhouse gas emissions in the decades to come and offering policy advice on when, where, and by how much to abate emissions. Some models are designed to offer a detailed portrayal of the climate, or the process of economic growth, or the feedback between these two systems; others focus on the long-run or the short-run, economic damages or environmental damages, carbon-based energy sectors or abatement technology. The best models produce results that inform and lend clarity to the climate policy debate. Some models surprisingly conclude – in direct contradiction of the urgency expressed in the scientific literature – that rapid, comprehensive emissions abatement is both economically unsound and unnecessary. And some models seem to ignore (and implicitly endorse the continuation of) gross regional imbalances of both emissions and income.

Good climate policy requires the best possible understanding of how climatic change will impact on human lives and livelihoods, in industrialized countries and in developing countries. No model gets it all right, but the current body of climate-economics models and theories contains most of the ingredients for a credible model of climate and development in an unequal world.

Unfortunately, many climate-economics models suffer from a lack of transparency, in terms of both their policy relevance and their credibility. Building a model of the climate and the economy inevitably involves numerous judgment calls; debatable judgments and untestable hypotheses turn out to be of great importance in determining the policy recommendations of climate-economics models, and should be visible for debate.

A good climate-economics model would be transparent enough for policy relevance, but still sophisticated enough to get the most important characteristics of the climate and the economy right. Unfortunately, many existing models fall short of one or both criterion: some are very complex – often entirely opaque to the non-specialist – and some represent the climate and economy incorrectly, as discussed below.

Our review of recent contributions to the climate-economics literature assesses 30 existing integrated assessment models (IAMs) in terms of four key aspects of the nexus of climate and the economy:

- choice of model structure and the type of results produced
- uncertainty in climate outcomes and the projection of future damages
- equity across time and space
- abatement costs and the endogeneity of technological change.

The next four sections of this review evaluate the body of existing climate economics models in terms of these key model characteristics, with illustrative examples of both problems and solutions taken from the literature. The concluding section summarizes our findings and their implications for the construction of climate-economics models.

## II. Choice of model structure

This review examines 30 climate-economics models, all of which have been utilized to make contributions to the IAM literature within the last ten years.<sup>1</sup> These models fall into five broad categories, with some overlap: welfare optimization, general equilibrium, partial equilibrium, simulation, and cost minimization (see Table 1).<sup>2</sup> Each of these structures has its own strengths and weaknesses, and each provides a different perspective on the decisions which are necessary for setting climate and development policy. In essence, each model structure asks a different question and that question sets the context for the results it produces.

**Table 1: Climate-economics models reviewed in this study**

Model Category	Global	Regionally Disaggregated
<b>Welfare Maximization</b>	DICE-2008 ENTICE-BR DEMETER-1CCS <i>MIND</i>	RICE-2004 FEEM-RICE FUND MERGE CETA-M GRAPE <i>AIM/Dynamic Global</i>
<b>General equilibrium</b>	JAM IGEM	IGS/EPPA SMG WORLDSCAN ABARE-GTEM G-CUBED/MSG3 MS-MRT AIM IMACLIM-R WIAGEM
<b>Partial Equilibrium</b>		MiniCAM <i>GIM</i>
<b>Simulation</b>		PAGE-2002 ICAM-3 E3MG <i>GIM</i>
<b>Cost Minimization</b>	GET-LFL <i>MIND</i>	DNE21+ MESSAGE-MACRO

Note: *Italics indicate that a model falls under more than one category*

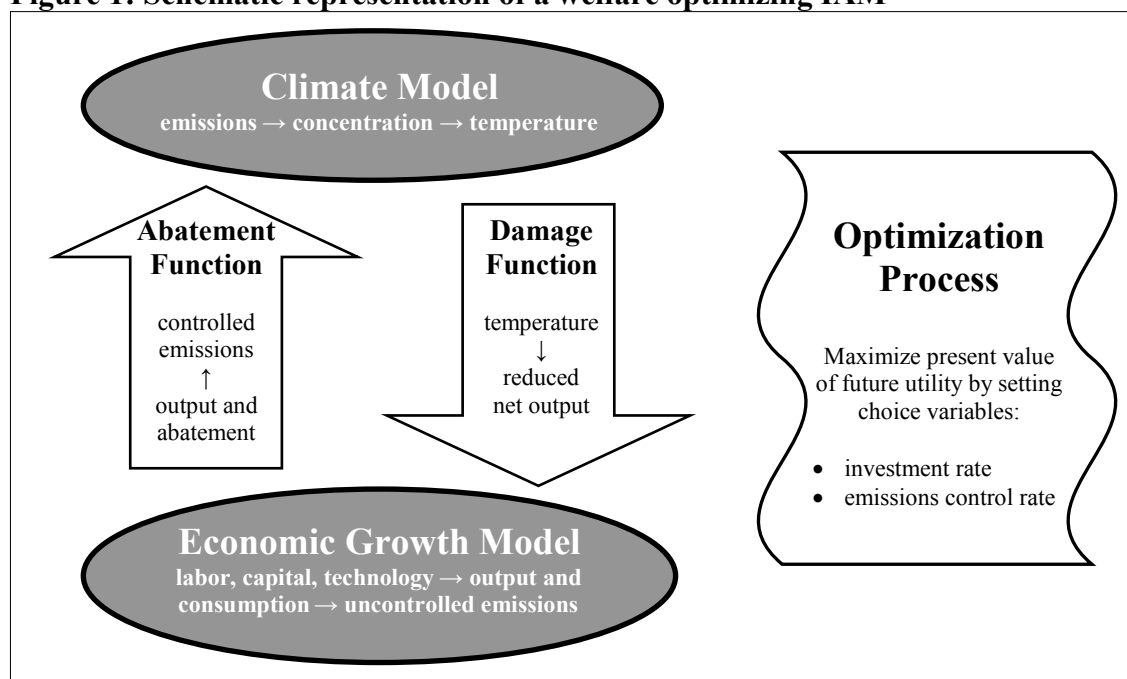
<sup>1</sup> Two climate-economics modeling projects published as special issues of the Energy Journal were indispensable in preparing this review. The first was organized by the Stanford Energy Modeling Forum (Weyant and Hill 1999) and the second by the Innovation Modeling Comparison Project (Edenhofer, Lessmann, Kemfert *et al.* 2006; Grubb *et al.* 2006; Köhler *et al.* 2006).

<sup>2</sup> A sixth category, macroeconomic models, could be added to this list, although the only example of a pure macroeconomic model being used for climate analysis may be the Oxford Global Macroeconomic and Energy Model (Cooper *et al.* 1999). Publically available documentation for this model is scarce and somewhat cryptic, perhaps because it was developed by a private consulting firm. Macroeconomic models include unemployment, financial markets, international capital flows, and monetary policy (or at least some subset of these) (Weyant and Hill 1999). Three general equilibrium or cost minimization models with macroeconomic features are included in this literature review, G-CUBED/MSG3, *MIND*, and MESSAGE-MACRO.

**Differences in model structures**

*Welfare optimization models* tend to be fairly simple, which adds to their transparency. Production causes both emissions and consumption. Emissions affect the climate, causing damages that reduce production. The models maximize the discounted present value of welfare (which grows with consumption, although at an ever-diminishing rate)<sup>3</sup> across all time periods by choosing how much emissions to abate in each time period, where abatement costs reduce production (see Figure 1). The process of discounting welfare (or “utility,” which is treated as a synonym for welfare here and in many models) requires imputing speculative values to non-market “goods” like ecosystems or human lives, as well as assigning a current value to future costs and benefits. Dynamic optimization models – including all of the welfare optimization and cost minimization models reviewed here – solve all time periods simultaneously, as if decisions could be made with perfect foresight.

**Figure 1: Schematic representation of a welfare optimizing IAM**



Our review of climate-economics models includes four global welfare optimization models – DICE-2007 (Nordhaus 2008), ENTICE-BR (Popp 2006), DEMETER-1CCS (Gerlagh 2006), and MIND (Edenhofer, Lessmann and Bauer 2006) – and seven regionally disaggregated welfare maximization models – RICE-2004 (Yang and Nordhaus 2006), FEEM-RICE (Bosetti *et al.* 2006), FUND (Tol 1999), MERGE (Manne and Richels 2004), CETA-M (Peck and Teisberg 1999), GRAPE (Kurosawa 2004), and AIM/Dynamic Global (Masui *et al.* 2006).

*General equilibrium models* represent the economy as a set of linked economic sectors (labor, capital, energy, etc.). These models are solved by finding a set of prices that have the effect of “clearing” all

<sup>3</sup> In these models, consumption’s returns to welfare are always positive but diminish as we grow wealthier. Formally, the first derivative of welfare is always positive and the second is always negative. A popular, though not universal, choice defines individual welfare, arbitrarily, as the logarithm of per capita consumption or income.

sectors simultaneously (that is, a set of prices that simultaneously satisfy demand and supply in every sector). General equilibrium models tend to use “recursive dynamics” – setting prices in each time period and then using this solution as the beginning point for the next period (thus assuming no foresight at all). Eleven general equilibrium models are reviewed in this study: JAM (Gerlagh 2008), IGEM (Jorgenson *et al.* 2004), IGSM/EPPA (Babiker *et al.* 2008), SMG (Edmonds *et al.* 2004), WORLDSCAN (Lejour *et al.* 2004), ABARE-GTEM (Pant 2007), G-CUBED/MSG3 (McKibbin and Wilcoxon 1999), MS-MRT (Bernstein *et al.* 1999), AIM (Kainuma *et al.* 1999), IMACLIM-R (Crassous *et al.* 2006), and WIAGEM (Kemfert 2001).

In dynamic versions of general equilibrium theory, multiple equilibria cannot always be ruled out (Ackerman 2002). When multiple equilibria are present, general equilibrium models yield indeterminate results which may depend on details of the estimation procedure. For this reason, an assumption of constant or decreasing returns is often added to their production functions, an arbitrary theoretical restriction which is known to assure a single optimal result (Köhler *et al.* 2006). Because increasing returns to scale are important to accurate modeling of endogenous technological change, general equilibrium modelers must skirt between oversimplifying their representation of the energy sector and allowing unstable model results. *Partial equilibrium models* – e.g. MiniCAM (Clarke *et al.* 2007) and GIM (Mendelsohn and Williams 2004) – make use of a subset of the general equilibrium apparatus, focusing on a smaller number of economic sectors by holding prices in other sectors constant; this procedure also can help to avoid problems with increasing returns to scale.

*Simulation models* are based on off-line predictions about future emissions and climate conditions; climate outcomes are not affected by the economic model. Rather, a predetermined set of emissions values by period dictates the amount of carbon that can be used in production, and model output includes the cost of abatement and cost of damages. Simulation models cannot, in and of themselves, answer questions of what policy makers *should* do to maximize social welfare or minimize social costs. Instead, the simulation models reviewed in this study – PAGE2002 (Hope 2006), ICAM-3 (Dowlatabadi 1998), E3MG (Barker *et al.* 2006), and GIM (Mendelsohn and Williams 2004) – estimate the costs of various likely future emission paths.

*Cost minimization models* are designed to identify the most cost effective solution to a climate-economics model. Some cost minimization models explicitly include a climate module, while others abstract from climate by representing only emissions, and not climatic change and damages. The four cost minimization models included in this review – GET-LFL (Hedenus *et al.* 2006), MIND (Edenhofer, Lessmann and Bauer 2006), DNE21+ (Sano *et al.* 2006), and MESSAGE-MACRO (Rao *et al.* 2006) – have very complex “bottom up” energy supply sectors, modeling technological choices based on detailed data about specific industries. Three of these models, excluding GET-LFL, combine a bottom-up energy supply sector with a top-down energy end-use sector, modeling technology from the vantage point of the macroeconomy.

### ***Evaluation of model structures***

The different types of model structures provide results that inform climate and development policy in very different ways. All five categories have strengths and weaknesses. Many of the best-known IAMs attempt to find the “optimal” climate policy, one that maximizes long-term human welfare. This

calculation depends on several unknowable or controversial quantities, including the numerical measurement of human welfare, the physical magnitude and monetary value of all current and anticipated climate damages, and the relative worth of future versus present benefits.

General equilibrium models can be extremely complex, combining very detailed climate models with intricate models of the economy; yet despite their detail, general equilibrium models' reliance on decreasing returns is a serious limitation to their usefulness in modeling endogenous technological change. Partial equilibrium models circumvent the problem of increasing returns, at the cost of a loss of generality. In some cases, there appears to be a problem of spurious precision in overly elaborated models of the economy, with, for example, projections of long-term growth paths for dozens of economic subsectors.

Simulation models are well suited for representing uncertain parameters and for developing IAM results based on well-known scenarios of future emissions, but their policy usefulness is limited by a lack of feedback between their climate and economic dynamics. Finally, cost minimization models address policy issues without requiring calculations of human welfare in money terms, but existing cost minimization models may suffer from the same tendency towards spurious precision exhibited in some general and partial equilibrium models.

### **III. Uncertain outcomes and projections of future damages**

IAMs inevitably rely on forecasts of future climate outcomes and the resulting economic damages, under conditions that are outside the range of human experience. This aspect of the modeling effort raises two related issues: the treatment of scientific uncertainty about climate change, and the functional relationships used to project future damages.

#### ***Scientific uncertainty in climate outcomes***

There are inescapable scientific uncertainties surrounding climate science, for instance in the climate sensitivity parameter (the temperature increase resulting from a doubling of CO<sub>2</sub> concentrations). As a result, low-probability, enormous-cost climate outcomes cannot be ruled out; the response to these extreme risks is often central to policy debate, and would ideally be incorporated in economic models of climate change. Yet we found that most IAMs use central or average estimates to set parameter values. Those few models that express parameter values as distributions most often use truncated distributions that inappropriately exclude or de-emphasize low-probability, high-cost catastrophes.

Uncertainty is inescapable, despite the ever-expanding body of climate research, because there are only a limited number of empirical observations relevant to questions such as estimation of the climate sensitivity parameter. As a result, the best estimates of the relevant probability distributions inevitably exhibit "fat tails," meaning that extreme outcomes are much more likely than a normal distribution would imply (Weitzman 2008). According to Martin Weitzman, an economist who has raised this problem in recent debate, IPCC (2007) data implies that an atmospheric concentration of 550 ppm of CO<sub>2</sub>-equivalent would lead to a 98<sup>th</sup> percentile chance of 6°C increase in temperature, a point at which we "are located in the terra incognita of ... a planet Earth reconfigured as science fiction... [where]

mass species extinctions, radical alterations of natural environments, and other extreme outdoor consequences will have been triggered by a geologically-instantaneous temperature change that is significantly larger than what separates us now from past ice ages.” (Weitzman 2007, p.716).<sup>4</sup>

In the face of such worst-case risks, it is misleading to look only at the most likely range of conditions. That approach would take for granted policy-makers’ willingness to play the odds in crafting a response to rising global emissions: Suppose that we knew that there were one hundred equally likely future scenarios, of which only one or a few would experience truly catastrophic climate change. The future will happen only once. If we plan well for the most likely outcomes but instead one that we consider unlikely comes to pass, will we be comforted by our parsimonious rationality?

The most common approach to uncertainty found in the IAM literature is off-line sensitivity analysis, often conducted by changing one parameter value at a time and observing the results. A more thorough treatment of uncertainty, through Monte Carlo analysis that varies multiple unknown parameters, is seen in just a few IAMs, and even then it is difficult to fully explore the parameter space, especially given the fat-tailed distributions that characterize many key climate parameters, and their poorly understood correlations.

One of the best-known models that incorporates Monte Carlo analysis of uncertain parameter values is the model used in the Stern Review (Stern et al. 2006) – Chris Hope’s PAGE2002 model (Hope 2006). PAGE2002 includes triangular distributions for 31 uncertain parameters; Hope’s standard analysis is based on 1000 iterations of the model; as in other multivariate Monte Carlo analyses, he uses Latin Hypercube sampling<sup>5</sup> to select the uncertain parameters. Even this modest level of sensitivity analyses has a major impact on results. For the Stern Review, introducing the Monte Carlo analysis instead of simply using the modal parameter values increases the expected value of annual climate damages by an average of 7.6 percent of world output (Dietz *et al.* 2007).

The 31 uncertain parameters in PAGE2002 include two sets of seven regional parameters, but there are still 19 orthogonal (that is, presumed unrelated or independent) parameters with independent distributions to be sampled for each iteration. This makes it essentially impossible for a Monte Carlo analysis to explore simultaneous worst cases in all or most of the parameters. To have, on average, at least one iteration with values from the worst quintile for all 19 parameters, it would be necessary to run the model an unimaginable 20 trillion times – a result of the so-called “curse of dimensionality” (Peck and Teisberg 1995). Of course, many parameters that are orthogonal in the model may be interdependent in the real world; for example, the warming that results from a doubling of carbon dioxide in the atmosphere and the release of natural carbon dioxide, or the scale of economic and non-economic benefits. A greater interdependency among parameters would make seemingly rare extreme events (based on multiple worst-case parameter values) more likely. But as long as these parameters are represented as orthogonal in probabilistic IAMs, a very high number of iterations will be necessary to assure even a single run with extreme values for all parameters. In PAGE2002, with just 1000

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<sup>4</sup> In more recent work, Weitzman has suggested that climate science implies even greater risks at the 95<sup>th</sup>-99<sup>th</sup> percentile (Weitzman 2008). Of course, his argument does not depend on an exact estimate of these risks; the point is that accuracy is unattainable and the risks do not have an obvious upper bound, yet effective policy responses must be informed by those low-probability extreme events.

<sup>5</sup> Latin Hypercube sampling, a technical procedure widely used in Monte Carlo analyses, ensures that the selected sets of parameters are equally likely to come from all regions of the relevant parameter space.



iterations, it is highly unlikely that there are any results for which more than a few parameters are assigned 95<sup>th</sup> percentile or worse values.

Only one other model among those reviewed has a built-in method of randomizing parameter values. Carnegie Mellon's ICAM is a stochastic simulation model that samples parameter values from probability distributions for 2000 parameters for an unspecified number of iterations (Dowlatabadi 1998). An enormous number of iterations would be necessary to assure even one result with low-probability values for any large subset of these parameters. With any plausible number of iterations, the "curse of dimensionality" means that the primary choice being made by the Monte Carlo sampling is the selection of which parameters happen to have their worst cases influence the results of the analysis. Suppose that worst-quintile values for a particular set of 5 parameters in PAGE2002, or 50 in ICAM, interact in a nonlinear manner to produce a catastrophe; it is extremely likely that a Monte Carlo analysis of merely a few thousand iterations would completely miss this interaction.<sup>6</sup>

Several studies have added a Monte Carlo analysis onto some of the other IAMs reviewed here.<sup>7</sup> Nordhaus and Popp (Nordhaus and Popp 1997) ran a Monte Carlo analysis on a modification of an earlier version of the DICE model – called PRICE – using eight uncertain parameters and 625 iterations, with five possible values for each of three parameters and a variation on Latin Hypercube sampling for the rest; again, so few iterations can reveal little about the tails of the distribution. Nordhaus also runs a Monte Carlo simulation of his more recent version of DICE-2007 (Nordhaus 2008) with eight parameters and 100 iterations, saying

We assume normal distributions primarily because we fully understand their properties. We recognize that there are substantial reasons to prefer other distributions for some variables, particularly ones that are skewed or have "fat tails," but introducing other distributions is highly speculative at this stage and is a more ambitious topic than the limited analyses that are undertaken here... (p.127-128)

Monte Carlo experiments exist in the literature for several other deterministic models. Kypreos (Kypreos 2008) adds five stochastic parameters to MERGE and runs 2500 iterations; Peck and Teisberg (Peck and Teisberg 1995) add one stochastic parameter to CETA-R with an unreported number of iterations; and Scott and co-authors (Scott *et al.* 1999) add 15 stochastic parameters to MiniCAM with an unreported number of iterations. Webster, Tatang and McRae (Webster *et al.* 1996) take a different approach to modeling uncertainty in ISGM/EPPA by using a collocation method that approximates the model's response as a polynomial function of the uncertain parameters.

None of the models reviewed here assume fat-tailed distributions and reliably sample the low-probability tails. Therefore, none of the models provide adequate information for formulating a policy response to the worst-case extreme outcomes that are unfortunately not unlikely enough to ignore.

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<sup>6</sup> If the uncertain parameters were all truly independent of each other, such combinations of multiple worst-case values would be extraordinarily unlikely. The danger is that the uncertain parameters, about which our knowledge is limited, may not be independent. If plausible events or research findings would lead to multiple worst-case values, then there is a risk which Monte Carlo analysis will usually miss due to the "curse of dimensionality." The greater the number of Monte Carlo parameters, the greater this risk becomes.

<sup>7</sup> For an earlier review of attempts to incorporate uncertainty in IAMs see (Scott *et al.* 1999).

### ***Projecting future damages***

Most IAMs have two avenues of communication between their climate model and their economic model: a damage function and an abatement function (see Figure 1 above). The damage function translates the climate model's output of temperature – and sometimes other climate characteristics, like sea-level rise – into changes to the economy, positive or negative.

Many models assume a simple form for this relationship between temperature and economic damage, such that damages rise in proportion to a power of temperature change:

$$1) \quad D = aT^b$$

where  $D$  is the value of damages (in dollars or as a percent of output),  $T$  is the difference in temperature from that of an earlier period, and the exponent  $b$  determines the shape or steepness of the curve. Implicitly, the steepness of the damage function at higher temperatures reflects the probability of catastrophe – a characteristic that can have a far more profound impact on model results than small income losses at low temperatures.

Our literature review revealed three concerns with damage functions in existing IAMs: The choice of exponents and other parameters for many damage functions are either arbitrary or under-explained; the form of the damage function constrains models' ability to portray discontinuities; and damages are commonly represented in terms of losses to income, not capital.

#### Arbitrary exponent

DICE, like a number of other models, assumes that the exponent in the damage function is 2 – that is, damages are a quadratic function of temperature change.<sup>8</sup> The DICE-2007 damage function was assumed to be a quadratic function of temperature change with no damages at 0°C temperature increase, and damages equal to 1.8 percent of gross world output at 2.5°C; this implies, for example, that only 10.2 percent of world output is lost to climate damages at 6°C. (Nordhaus 2007a).<sup>9</sup> Numerous subjective judgments, based on fragmentary evidence at best, are incorporated in the point estimate of 1.8 percent damages at 2.5°C (much of the calculation is unchanged from (Nordhaus and Boyer 2000), which provides a detailed description). The assumption of a quadratic dependence of damage on temperature rise is even less grounded in any empirical evidence.

Many models assert key parameters, like those of the damage function, with little or no explanation or justification. The GRAPE model (Kurosawa *et al.* 1999, p.163), for example, asserts its damage function parameters without any justification, but concedes that “It is an open question how climate change impacts should be assessed qualitatively and quantitatively.” The MERGE model attributes its damage parameters to “the literature” (Manne and Richels 2004); Manne and Richels comment that, “Admittedly, the parameters of this loss function are highly speculative. With different numerical

<sup>8</sup> DICE-2007 actually uses a slightly more complicated equation which is equivalent to our equation 1), with the exponent  $b=2$ , for small damages.

<sup>9</sup> See (Ackerman *et al.* 2008) for a more detailed critique of the DICE-2007 damage function.

values, different abatement policies will be optimal. This helps to explain why there is no current international consensus on climate policy.” (p.2-3)

Our review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function – although the practice is endemic in IAMs, especially in those that optimize welfare. PAGE2002 (Hope 2006) uses a damage function calibrated to match DICE, but makes the exponent an uncertain (Monte Carlo) parameter, with minimum, most likely, and maximum values of 1.0, 1.3, and 3.0, respectively. Sensitivity analyses of the Stern Review (Stern et al. 2006) results, which were based on PAGE2002, show that fixing the exponent at 3 – assuming damages are a cubic function of temperature – increases annual damages by a remarkable 23 percent of world output (Dietz *et al.* 2007). Thus the equally arbitrary assumption that damages are actually a cubic function of temperature rather than quadratic would have a very large effect on IAM results, and consequently on their policy implications.

### Continuity

Damage functions are often defined to be continuous across the entire range of temperature rise, even though it is far from certain that climate change will in fact be gradual and continuous. Several climate feedback processes point to the possibility of an abrupt discontinuity at some uncertain temperature threshold or thresholds. However, only a few IAMs instead model damages as discontinuous, with temperature thresholds at which damages jump to much worse, catastrophic outcomes.

Two leading models incorporate some treatment of catastrophic change, while maintaining their continuous, deterministic damage functions. MERGE (Manne and Richels 2004) assumes all incomes fall to zero when the change in temperature reaches 17.7 °C – which is the implication of the quadratic damage function in MERGE, fit to its assumption that rich countries would be willing to give up 2 percent of output to avoid 2.5 °C of temperature rise. This formulation deduces an implicit level of catastrophic temperature increase, but maintains the damage function’s continuity. DICE-2007 (Nordhaus 2007b) models catastrophe in the form of a specified (moderately large) loss of income, which is multiplied by a probability of occurrence (an increasing function of temperature), to produce an expected value of catastrophic losses. This expected value is combined with estimates of non-catastrophic losses, to create the DICE damage function; that is, it is included in the quadratic damage function discussed above.

In the PAGE2002 model (Hope 2006), the probability of a catastrophe increases as temperature rises above some specified temperature threshold. The threshold at which catastrophe first becomes possible, the rate at which the probability increases as temperature rises above the threshold, and the magnitude of the catastrophe when it occurs, are all Monte Carlo parameters with ranges of possible values.

### Income damages

Damages are commonly modeled in IAMs as losses to income or consumption, leaving capital stocks and productivity undiminished for future use. For example, non-catastrophic damages in the DICE-

2007 model (Nordhaus 2007a) include impacts to agriculture, “other vulnerable markets”, coastal property from sea-level rise, health, time-use, and “human settlements and natural ecosystems”, all of which are subtracted directly from total economic output. Many of these categories seem more like reductions to capital than income, especially coastal property and human settlements damages. Others seem like they would have multi-period effects on the marginal productivity of capital or labor, that is, the ability of technology to transform capital and labor into income; damages to agricultural resources and health are good examples of longer-term changes to productivity.

When damages are subtracted from output, the implication is that these are one time costs that are taken from consumption, with no effects on capital, production, or consumption in the next period – an unrealistic assumption even for the richest countries, as attested by the ongoing struggle to rebuild New Orleans infrastructure, still incomplete three years after Hurricane Katrina. FUND (Tol 1999) is unusual among welfare optimizing IAMs in that it models damages as one-time reductions to both consumption and investment, where damages have lingering “memory” effects determined by the rate of change of temperature increase.

It would be possible to develop an IAM that modeled climate damages as, at least in part, losses of capital stock and/or decreases in productivity. This would require a model design only slightly more complicated than the common structure sketched in Figure 1: climate damages would alter the inputs to the production function that determines output, or the parameters of that function which express productivity, rather than just reducing the amount of available output after it is constructed. It would build in “memory,” with multi-period consequences of major climate impacts, a realistic feature that could be implemented relatively transparently.

#### **IV. Equity across time and space**

Most climate economic models implicitly assume that little attention is needed to the problems of equity across time and space. In the area of intertemporal choice, most models have high discount rates that inflate the importance of the short-term costs of abatement relative to the long-term benefits of averted climate damage. Together with the common assumption that the world will grow richer over time, discounting gives greater weight to earlier, poorer generations relative to later, wealthier generations.

Equity between regions of the world, in the present or at any moment in time, is intentionally excluded from most IAMs, even those that explicitly treat the regional distribution of impacts. In such regionally disaggregated models, any simple, unconstrained attempt to maximize human welfare would generate solutions that include large transfers from rich to poor regions. To prevent this “problem” from dominating their results, IAMs employ “Negishi welfare weights” (based on theoretical analysis in (Negishi 1972)), which constrain possible solutions to those which are consistent with the existing distribution of income. In effect, the Negishi procedure imposes an assumption that human welfare is more valuable in richer parts of the world.

### ***Equity across time***

The impacts of climate change, and of greenhouse gas mitigation, will stretch centuries or even millennia into our future. Models that estimate welfare, income, or costs over many years must somehow value gains and losses from different time periods. The early work of Frank Ramsey (Ramsey 1928) provides the basis for the widely used “prescriptive” approach, in which there are two components of the discount rate: the rate of pure time preference, or how human society feels about costs and benefits to future generations, regardless of the resources and opportunities that may exist in the future; and a wealth-based component – an elasticity applied to the rate of growth of real consumption – that reflects the diminishing marginal utility of income over time as society becomes richer.

Algebraically, the discount rate,  $r(t)$ , combines these two elements: it is the rate of pure time preference,  $\rho$ , plus the product of the elasticity of marginal utility with respect to consumption per capita,  $\eta$ , and the growth rate of income or consumption per capita,  $g(t)$ .

$$2) \quad r(t) = \rho + \eta g(t)$$

Because climate change is a long-term problem involving long time lags, climate-economics models are extremely sensitive to relatively small changes in the assumed discount rate. There are long-standing debates on the subject, which are summarized well in the Stern Review (Stern et al. 2006). Remarkably, given the prominence of the discount rate debates, the model descriptions for many IAMs do not state the discount rate they use, or any of its components. Indeed, a number of papers refer to discounting but offer no information about the rates and methodologies they use. Some use the alternative, “descriptive” approach to discounting, where the market rate of interest or capital growth is taken to represent the discount rate.<sup>10</sup> These analyses typically either set the discount rate at 5 percent, or at an unspecified market rate of interest (for example, Charles River Associates’ MS-MRT (Bernstein *et al.* 1999), a general equilibrium model).

Choices about the discount rate inevitably reflect value judgments made by modelers. The selection of a value for the pure rate of time preference is a problem of ethics, not economic theory or scientific fact. Pure time preference of 0 would imply that (holding real incomes constant) benefits and costs to future generations are just as important as the gains and losses that we experience today. The higher the rate of pure time preference, the less we value harm to future generations from climate change and the less we value the benefits that we can confer on future generations by averting climate change. Pure rates of time preference found in this literature review range from 0.1 percent in the Stern Review’s PAGE2002 analysis (Hope 2006) to 3 percent in RICE-2004 (Yang and Nordhaus 2006).

Only a few model descriptions directly state their elasticity of marginal utility of consumption and growth rate, although the use of this elasticity, implying that marginal utility declines as consumption grows, is common to many IAMs. In DICE-2007 (Nordhaus 2008), the pure rate of time preference is 1.5 percent, elasticity of the marginal utility of consumption is set at 2, and per capita consumption begins growing at 1.6 percent per year but slows to 1 percent over the course of 400 years. The total discount rate for DICE-2007, therefore, declines from 4.7 percent in 2005 down to 3.5 percent in 2395. In the Stern Review’s version of PAGE2002 (Hope 2006), the pure rate of time preference is 0.1

<sup>10</sup> The terminology of descriptive and prescriptive approaches was introduced and explained in (Arrow *et al.* 1996).

percent, the elasticity of the marginal utility of consumption is set at 1, and the growth in per capita consumption averages 1.3 percent, for a total discount rate of 1.4 percent.

A higher elasticity of marginal utility of income reflects a greater emphasis on equity: as long as the elasticity is greater than zero, an increase in income or consumption to a poorer person is worth more to our social welfare than the same absolute increase in income to a richer person.<sup>11</sup> PAGE2002's elasticity of 1 implies a logarithmic utility function. When utility is assumed to be equal to the logarithm of per capita income, a percentage change in income has the same effect on utility regardless of the level of income. For example, a \$100 increase to the income of someone with an income of \$1000 would have the same impact on utility as a \$1 million increase to the income of someone with \$10 million.

DICE-2007's elasticity of 2 indicates that utility is proportional to 1 minus the inverse of per capita consumption – a function that is more concave than the natural log – which therefore places a greater emphasis on improvements to income for those at low income levels. Because DICE is a global model – lacking regional disaggregation – there is only one utility function for the world as a whole; the practical upshot of this is that the diminishing marginal utility of income is applicable only in comparisons across time (e.g. the present generation versus the future) and not in comparisons across different regions or socio-economic characteristics (e.g. Africa versus North America today, or at any given point in time).

The four cost minimization models included in this literature review – GET-LFL (Hedenus *et al.* 2006), MIND (Edenhofer, Lessmann and Bauer 2006), DNE21+ (Sano *et al.* 2006), and MESSAGE-MACRO (Rao *et al.* 2006) – all report a 5 percent discount rate.<sup>12</sup> The ethical issues involved in discounting abatement costs are somewhat more straightforward than those involved in discounting welfare. Abatement technologies have well-defined monetary prices, and thus are more firmly situated within the theoretical framework for which discounting was developed. Many abatement costs would occur in the next few decades – over spans of time which could fit within the lifetime and personal decisions of a single individual. To pay for \$1000 worth of abatement fifty years from now, for example, one can invest \$230 today in a low-risk bond with 3 percent annual interest. On the other hand, welfare optimization models must inevitably assign subjective, contestable values to the losses and gains to future generations that are difficult to monetize, such as the loss of human life or the destruction of ecosystems. No investment today can adequately compensate for a loss of life or irreversible environmental damage; and even if an agreeable valuation were established, there is no existing, or easily imagined, mechanism for compensating victims of climate change several hundred years in the future.

### ***Equity across space***

IAMs that optimize welfare for the world as a whole – modeled as one aggregate region – maximize the result of a single utility function by making abatement and investment choices that determine the

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<sup>11</sup> If the elasticity of the marginal utility of consumption is a constant  $\eta$ , as in equation 2), and per capita consumption is  $c$ , then utility =  $c^{(1-\eta)/(1-\eta)}$ , except when  $\eta=1$ , when utility =  $\ln c$ . See the Stern Review technical annex to Chapter 2 on discounting or other standard works on the subject for explanation (Stern *et al.* 2006).

<sup>12</sup> The MIND model (Edenhofer, Lessmann and Bauer 2006), which combines cost minimization with welfare maximization, uses a pure rate of time preference of 1 percent and a total discount rate of 5 percent.

emissions of greenhouse gases; emissions then determine climate outcomes and damages, one of the inputs into utility. This utility function is a diminishing function of per capita income or per capita consumption. The IAM chooses emission levels for all time periods simultaneously – when more emissions are allowed, future periods lose income to climate damages; when emissions are lowered, abatement costs decrease current income.

The model's optimizing protocol (or more picturesquely, the putative social planner) balances damages against abatement costs with the goal of maximizing utility – not income or consumption. Because utility is modeled with diminishing returns to income, the additions and subtractions to income caused by climate change are only one input into the optimizing decision. The optimal result also depends on the per capita income level of the time period in which the change to income occurs. A change to income in a rich time period is given a lower weight than an identical change to income in a poor time period (even if the rate of pure time preference is zero). If, as usual, per capita income and consumption are projected to keep growing, the future will be richer than the present. Under that assumption, a more rapidly diminishing marginal utility of income means that the richer future matters less, in comparison to the relatively poorer present.

Regional welfare optimizing IAMs apply the same logic, but with separate utility functions for each region. The model is solved by choosing abatement levels that maximize the sum of utility in all regions. Seemingly innocuous, the disaggregation of global IAMs into component regions raises a gnarly problem for modelers: with identical, diminishing marginal returns to income in every region, the model can increase utility by moving income towards the poorest regions – whether in allocating regionally specific damage and abatement costs, or inducing transfers between regions for the purpose of fostering technical change, or funding adaptation, or purchasing emission allowances, or any other channel available in the model for inter-regional transfers.

Modelers have typically taken this tendency toward equalization of income as evidence of the need for a technical fix. In order to model climate economics without any distracting rush toward global equality, many models apply the little-known technique of “Negishi weights.” (Negishi 1972) Stripped of its complexity, the Negishi procedure assigns larger weight to the welfare of richer regions, thereby eliminating the global welfare gain from income redistribution. For examples of how this procedure is discussed in the climate-economics literature see (Kypreos 2005, p.2723; Peck and Teisberg 1997, p.4; Yang and Nordhaus 2006, p.738, 731).

In more detail, the technical fix involves establishing a set of weights for the regional utility functions. The model is run first with no trade or financial transfers between regions; the regional pattern of per capita income and marginal product of capital from that autarkic (no-trade) run is then used to set the so-called Negishi weights, for each time period, that equalize the marginal product of capital across all regions. Since the marginal product of capital is higher in lower-income regions, the Negishi weights give greater importance to utility in higher-income areas. In a second iteration, the normal climate-economics model, with transfers possible between regions, is restored, and the Negishi weights are hard-wired into the model's utility function. The result, according to the model descriptions, is that the models act as if the marginal product of capital were equal in all regions and, therefore, no transfers are necessary to assuage the redistributive imperative of diminishing marginal returns. (For an example of the Negishi weights methodology see (Yang and Nordhaus 2006) or (Manne and Richels

2004).) The (usually) unspoken implication is that the models are acting as if human welfare is more valuable in the richer parts of the world.

Describing the addition of Negishi weights to regional welfare optimization models as a mere technical fix obscures a fundamental assumption about equity. Negishi weights cause the models to maximize welfare as if every region already had the same income per capita – suppressing the obvious reality of vastly different regional levels of welfare, which the models would otherwise highlight and seek to alleviate (Keller *et al.* 2003; Manne 1999; Nordhaus and Yang 1996).

In IAMs that do not optimize welfare, assumptions regarding the interregional effects of a diminishing marginal utility of income are not negated by Negishi weights. For example, in the PAGE2002 (Hope 2006) model – a simulation model that reports regional estimates – no radical equalization of per capita income across regions occurs because utility is not maximized.<sup>13</sup> In a recent assessment of the Stern Review (Stern *et al.* 2006), Partha Dasgupta (Dasgupta 2007) argues on equity grounds that the PAGE2002 model has an insufficient elasticity of the marginal utility of consumption (recall that PAGE uses  $\eta=1$ ) – or too little emphasis on interregional equity; Dasgupta advocates an  $\eta$ , or elasticity of marginal utility of income, in the range of 2 to 4 (and advocates, as well, the income transfers that would result from that elasticity in a non-Negishi world).

By including discounting over time as well as Negishi weights, welfare optimizing IAMs accept the diminishing marginal utility of income for intergenerational choices, but reject the same principle in the contemporary, interregional context. Some justification is required if different rules are to be applied in optimizing welfare across space than those used when optimizing welfare across time. At the very least, a climate-economics model's ethical implications should be transparent to the end users of its analyses. While ethical concerns surrounding discounting have achieved some attention in policy circles, the highly technical but ethically crucial Negishi weights are virtually unknown outside the rarified habitat of integrated assessment modelers and theoretical welfare economists. The Negishi procedure conceals one strong, controversial assumption about welfare maximization, namely that existing regional inequalities are not legitimate grounds for shifting costs to wealthier regions, but inequalities across time are legitimate grounds for shifting costs to wealthier generations. Other assumptions, needless to say, could be considered.

#### **IV. Abatement costs and the endogeneity of technological change**

The analysis of abatement costs and technological change is crucial to any projection of future climate policies. An unrealistic picture of fixed, predictable technological change, independent of public policy, is often assumed in IAMs – as is the treatment of investment in abatement as a pure loss. These choices are mathematically convenient, but prevent analysis of policies to promote and accelerate the creation of new, low-carbon technologies. This oversimplification supports the questionable conclusion that the best policy is to avoid immediate, proactive abatement, and wait for automatic technical progress to reduce future abatement costs.

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<sup>13</sup> Earlier versions of PAGE2002, in fact, applied equity weights that boost the relative importance of outcomes in developing countries; the Stern Review modeling effort dropped the equity weights in favor of a more explicit discussion of regional inequality (Chris Hope, personal communication, 2008).



### ***Choices in modeling abatement technology***

There have been rapid advances in recent years in the area of modeling endogenous technological change. A review by the Innovation Modeling Comparison Project (Edenhofer, Lessmann, Kemfert *et al.* 2006; Grubb *et al.* 2006; Köhler *et al.* 2006) offers a very thorough description of the most recent attempts to model endogeneity and induced technological innovation – an effort that we will not attempt to reproduce here. Instead, this section briefly discusses three choices that all IAM modelers must make with regard to their representation of abatement technology: how to model increasing returns; how much technological detail to model; and how to model macroeconomic feedback.

Many models, especially general equilibrium models, assume technologies are characterized by decreasing returns to scale (meaning that doubling all inputs yields less than twice as much output), a provision which ensures that there is only one, unique equilibrium result. The assumption of decreasing returns may be realistic for resource-based industries such as agriculture or mining, but it is clearly inappropriate to many new, knowledge-based technologies – and indeed, it is inappropriate to many branches of old as well as new manufacturing, where bigger is better for efficiency, up to a point. Some industries exhibit not only increasing returns in production, but also “network economies” in consumption – the more people that are using a communications network or a computer operating system, the more valuable that network or operating system is to the next user.

The problem for modeling is that increasing returns and network economies introduce path dependence and multiple equilibria into the set of possible solutions. Small events and early policy choices may decide which of the possible paths or output mixes the model will identify as “the solution”. An inferior computer operating system, energy technology, or other choice may become “locked in” – the established standard is so widely used, and so low-priced because it is produced on such a large scale, that there is no way for individual market choices to lead to a switch to a technologically superior alternative. Modeling increasing returns, path dependence, and multiple equilibria can bring IAMs closer to a realistic portrayal of the structure and nature of emissions abatement and economic development options, but at the expense of making models more difficult to construct and model results more difficult to interpret.

Knowledge spillovers are also related to increasing returns. Some of the returns to research and development are externalities, that is, they impact on third parties – other companies, industries, or countries. Because of the public goods character of knowledge, its returns cannot be completely appropriated by private investors. Without public incentives for research and development, private firms will tend to under-invest in knowledge, with the result that the total amount of research and development that occurs is less than would be socially optimal.

Increasing returns are modeled either as a stock of knowledge capital that becomes an argument in the production function, or as learning curves that lower technological costs as cumulative investments in physical capital or research and development grow.

A second choice that IAM modelers must make is how much technological detail to include. This encompasses not only whether to model increasing returns but also how many regions, industries, fuels, abatement technologies, or end uses to include in a model. A more detailed technology sector can improve model accuracy but there are limits to the returns from adding detail – at some point, data requirements, spurious precision, and loss of transparency begin to detract from a model’s usefulness.

On the other hand, a failure to model sufficient technological diversity can skew model results. Abatement options such as renewable energy resources, energy efficiency technologies, and behavioral shifts serve to limit abatement costs; models without adequate range of abatement options can exaggerate the cost of abatement, and therefore recommend less abatement effort, than a more complete model would.

The final modeling choice is how to portray macroeconomic feedback from abatement to economic productivity. A common approach is to treat abatement costs as a pure loss of income, a practice that is challenged by new models of endogenous technological change, but still employed in a number of IAMs, such as DICE-2007 (Nordhaus 2008). Two concerns seem of particular importance. Modeling abatement costs as a dead-weight loss implies that there are no “good costs” – that all money spent on abatement is giving up something valuable and thereby diminishing human welfare. But many costs do not fit this pattern: money spent wisely can provide jobs or otherwise raise income, and can build newer, more efficient capital. A related issue is the decision to model abatement costs as losses to income. Abatement costs more closely resemble additions to capital, rather than subtractions from income. (A similar argument can be made regarding many kinds of damage costs: see the earlier section on projecting future damages.)

### ***Cost minimization models***

Many of the IAMs making the most successful inroads into modeling endogenous technological change are cost minimization models. All four of the cost minimization models reviewed in this study – GET-FL (Hedenus *et al.* 2006), DNE21+ (Sano *et al.* 2006), MIND (Edenhofer, Lessmann and Bauer 2006), and MESSAGE-MACRO (Rao *et al.* 2006) – include learning curves for specific technologies and a detailed rendering of alternative abatement technologies.

GET-FL, DNE21+, MIND, and MESSAGE-MACRO are all energy systems models that include greenhouse gas emissions but not climate change damages. These models include various carbon-free abatement technologies, carbon capture and storage, and spillovers within clusters of technologies. GET-FL has learning curves for energy conversion and investment costs. DNE21+ has learning curves for several kinds of renewable energy sources and a capital structure for renewables that is organized in vintages. Both MIND and MESSAGE-MACRO combine an energy system model with a macroeconomic model. MIND has learning curves for renewable energy and resource extraction research; development investments in labor productivity; trade-offs between different types of research and development investment; and a vintaged capital structure for renewables and carbon capture and storage technologies. MESSAGE-MACRO models interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services; declining costs in extraction and production; and learning curves for several energy technologies (Edenhofer, Lessmann, Kemfert *et al.* 2006; Köhler *et al.* 2006).

These energy system models demonstrate the potential for representing induced innovation and endogeneity in technological change. Unfortunately, the very fact of their incredible detail of energy resources, technologies and end uses leads to a separate problem of unmanageably large and effectively opaque results in the most complex IAMs. (For example, the RITE Institute’s DNE21+ models historical vintages, eight primary energy sources and four end-use energy sectors, along with

five carbon capture and storage methods, several energy conversion technologies, and separate learning curves for technologies like wind, photovoltaics and fuel cells.) A model is constructed at the level of detail achievable from present day energy sector data, providing accuracy in the base year calculations. Then the model is extended into the future based on unknowable and untestable projections, turning historical accuracy into spurious precision in future forecasts. A high level of specificity about the future of the energy sector cannot be sustained over the number of years or decades necessary to analyze the slow, but inexorable, advance of climate change.

## VI. Conclusions

The best-known climate-economics models weigh the costs of allowing climate change to continue against the costs of stopping or slowing it, and thus recommend a “best” course of action: one that, given the assumptions of the model, would cause the least harm. The results of such models are, of course, only as good as their underlying structures and parameter values.

Analysis of climate change, in economics as well as in science, inescapably involves extrapolation into the future. To understand and respond to the expected changes, it is essential to forecast what will happen at greenhouse gas concentrations and temperature levels that are outside the range of human experience, under regimes of technological progress and institutional evolution that have not yet even been envisioned. While some progress has been made toward a consensus about climate science modeling, there is much less agreement about the economic and societal laws and patterns that will govern future development.

IAMs seek to represent both the impacts of changing temperature, sea level, and weather on human livelihoods, and the effects of public policy decisions and economic growth on greenhouse gas emissions. IAMs strive not only to predict future economic conditions but also to portray how we value the lives, livelihoods, and natural ecosystems of future generations – how human society feels about those who will inherit that future. The results of economic models depend on theories about future economic growth and technological change, and on ethical and political judgments.

Model results are driven by conjectures and assumptions that do not rest on empirical data and often cannot be tested against data until after the fact. To the extent that climate policy relies on the recommendations of IAMs, it is built on what looks like a “black box” to all but a handful of researchers. Better-informed climate policy decisions might be possible if the effects of controversial economic assumptions and judgments were visible, and were subjected to sensitivity analyses.

Our review of the literature has led to several concrete lessons for model development:

- Many value-laden technical assumptions are crucial to policy implications, and should be visible for debate. Existing models often bury assumptions deep in computer code and parameter choices, discouraging discussion. Ultimately, results are often driven by these core assumptions, rather than by the technical apparatus.
- Crucial scientific questions – like the value of the climate sensitivity parameter and the threshold and probability for huge, irreversible catastrophe – remain uncertain. Most IAMs use

central or average estimates, and ignore catastrophic risk. Those few that use Monte Carlo analysis often truncate distributions, de-emphasizing or excluding low-probability, high-cost outcomes. A broader embrace of the full range of uncertainty is required, and will likely lead to different results.

- Modeling climate economics requires the projection of damages at temperatures outside the historical experience. Many models arbitrarily assume that damages grow as the square of temperature change, calibrated to one or two speculative point estimates of low-temperature damages. Almost all models treat climate damages as losses of current income rather than decreases in capital stock. Alternative assumptions, which are at least as plausible, would lead to much greater estimates of damages, and more urgency about policies to address the problem.
- Today's actions affect the climate and economy of future generations, thus linking current and future welfare. Many models have high discount rates, inflating the importance of short-term abatement costs while trivializing long-term benefits of mitigation. A positive rate of pure time preference is common but controversial. As is widely recognized, a lower discount rate values the future more fully, and justifies an "optimal" policy of doing more, sooner, to mitigate climate change.
- Climate choices occur in an unequal world and inevitably affect opportunities for development. Most regionally disaggregated models use a technical device ("Negishi welfare weights") that freezes the current income distribution, constraining models to ignore the welfare benefits of movement toward inter-regional equality. Without this artificial limitation, modeling of climate and development would place much greater weight on the impacts on low-income regions.
- Measures to induce or accelerate technological change will be crucial for a successful climate policy. Many IAMs model decreasing returns or assume that technological progress is exogenous, and treat abatement costs as an unproductive loss of income, not an investment in energy-conserving capital. Models of endogenous technical change and increasing returns are more complex but more realistic, allowing path dependence and multiple equilibria.

This review has highlighted several of the key shortcomings typically found in many of the climate-economics models that are currently being used to inform climate policy. The models have improved over the years, including expanded treatment of externalities, technological innovation, and regional disaggregation. But there is still tremendous scope for further improvement, including more extensive sensitivity analyses and more rigorous examination of risk and uncertainty. And fundamentally subjective judgments, especially those that embody deeply value-laden assumptions, can be made more explicit.

What difference would it make to change these features of climate economics modeling? In the absence of a better model, we can only speculate about the results. Our guess is that the modifications we have proposed would make a climate economics model more consistent with the broad outlines of climate science models, portraying the growing seriousness of the problem, the ominous risks of catastrophe, and the need for immediate action.

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