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Projections Regarding Climate Change and Development

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Introduction

There is a circular relationship between greenhouse gas emissions and development: economic development results in higher output and more emissions; emissions cause climate change – higher temperatures, changes to precipitation, more extreme storms, and less predictable weather overall – which in turn cause economic damage; and finally, completing the circle, changes to economic output cause changes in emissions. Given today's industrial, power-generation, and transportation technologies, economic development can be said to require greenhouse gas emissions. At the same time, climate change will have the worst impacts in the least developed countries where the cost of adaptation measures (to protect populations from the worst effects of climate change) may be prohibitive.

Global agreements on emissions that fail to consider the distribution of income and wealth among countries will impede economic development in low and middle-income countries. Without large-scale investments in abatement and adaptation measures, climate change will have devastating economic and social effects, especially in the poorest nations.

In many common climate economics models, emissions scenarios are used to project the likely scale of economic damages and losses due to climate change. When infrastructure is destroyed and productivity is interrupted, the effect is slower projected economic growth and lower future output. The economic output in each time period in turn drives projected emissions. Efforts to reduce emissions and adapt to the worst impacts of climate change are costly. Investment in abatement and adaptation is often modeled as a zero-sum-game, resulting in losses to investment in future production and further reductions in future output. In both industrialized and developing countries, however, investments in emissions abatement and climate impact adaptation, far from squeezing out other forms of investment, may have the potential to drive economic development. Emissions abatement may take the form of cutting edge electricity generation and distribution technology. Climate impact adaptation is often synonymous with improvements to infrastructure and protection from natural disasters.

Climate stabilization and economic development are separate challenges which require a joint global response. Neither problem can be ignored – and neither one can be solved in isolation from the other. Economic development without concern for climate change would hasten the impending crisis in which a worsening climate may make the earth unable to support human society and modern economic life. Conversely, climate protection without concern for development would lock in existing inequities and conflicts – and it is impossible, in any case, for climate policy to ignore the rapid growth already underway in a number of developing countries.

Overview of literature review

There is no shortage of models that join climate to economy with the goal of predicting emissions, economic growth, and climate damages 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.

This review examines 30 climate-economics models, all of which have been utilized to make contributions to the integrated assessment model (IAM) literature within the last ten years.[1] These models fall into five broad categories, with some overlap: welfare optimization, general equilibrium, partial equilibrium, simulation, and cost minimization (see Table 1).

[1] Two climate-economics modeling projects published as special issues of the Energy Journal were indispensible 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).

Table 1: Climate-Economics Models Reviewed in this Study

[redacted]

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. [2]

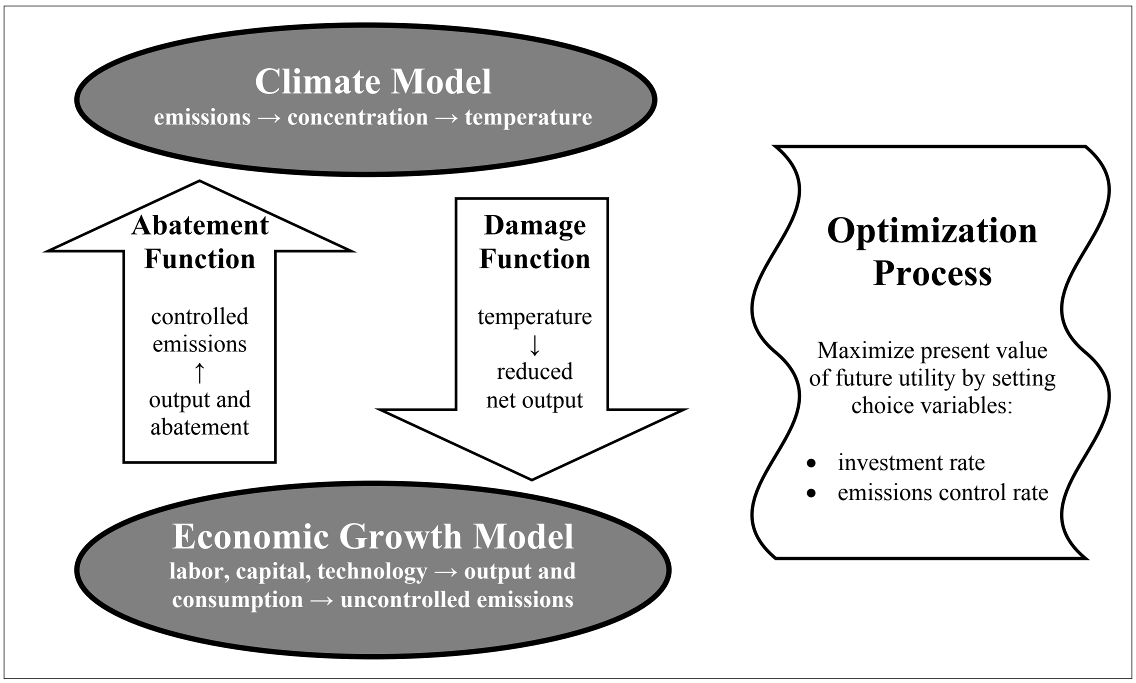
Differences in model structures

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

[2] 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.

(which grows with consumption, although at an ever-diminishing rate)[3] 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 sectors simultaneously (that is, a set of prices that simultaneously satisfy demand

[3] 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.

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 Wilcoxen 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

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.

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.

Four questions in climate and development policy

Development policy discussion frequently focuses on trade liberalization to allow export-led economic growth, and micro-level humanitarian assistance to the world's poorest regions. While removal of trade restrictions has helped some countries, and provision of famine relief, anti-mosquito bed nets, and the like have helped others, these policies are not enough to solve the deep problems of underdevelopment. Much more will be needed to start growth in economies that are stagnating, and to steer growth in a climate-friendly direction in economies that are surging ahead.

Climate policy discussion has proceeded along a different track. Dire warnings from climate scientists have led some countries to adopt ambitious targets for emission reduction, but these remain largely abstract, long-term goals. Practical policy debate focuses on the mechanics of carbon taxes or trading schemes, and on the fear that ambitious climate initiatives will prove too expensive, constraining economic growth. The IAMs of climate economics give the discussion an aura of quantitative rigor and precision, while typically endorsing an overly cautious approach of starting very slowly. While concerned with overall costs, IAMs generally have nothing to say about regional inequality and development.

Climate and development policy, both in practice and in the analytical literature, often conflates several of the questions that climate economic models attempt to answer: the need for global emissions reductions, for abatement measures in any one country, and for financial investments in abatement and adaptation – essentially, the when, where, and by how much of emissions abatement. For clarity, the results of IAMs – and the central themes of climate and development policy – can be addressed as four separate questions:

- How much emissions reductions should take place by when? Or, what is the maximum level of global emissions allowable in each time period?
- Where should these emission reductions (and emissions) take place?
- Who should pay for emissions reductions and adaptation measures?
- In the absence of climate policy, what is likely to happen?

In our assessment of the climate and development literature we will address each of these questions in turn.

1. How much emissions reductions should take place by when?

The maximum level of global emissions allowable in each time period is both a matter for scientific determination and a choice by policy makers of what emissions reductions are best for humanity. The scientific literature makes it clear that there are thresholds of greenhouse gas emissions, atmospheric concentrations, and global temperatures that should not be crossed, even if some residual uncertainty remains about the precise concentrations or temperatures at which these thresholds occur. The results of exceeding these thresholds are severe, long-reaching and potentially irreversible. The decisions of policy makers often take into account both direct scientific predictions and the indirect predictions of IAMs, which interpret climate science in economic terms. The results of IAMs are heavily dependent on modeling assumptions regarding the discount rate, uncertainty, the likely scale of damages, and projections of economic growth.

1a. What does the scientific literature tell us about thresholds not to be crossed?

It is increasingly accepted that there are critical thresholds at which climate change may trigger abrupt, irreversible, large-scale damages. Unfortunately, there is no firm estimate of the temperatures or greenhouse gas concentrations at which these discontinuous events will occur. The four Intergovernmental Panel on Climate Change (IPCC) assessment reports to date have grown steadily more ominous in their discussion of risks of abrupt climate change. The 2007 report (IPCC 2007, Ch. 19) projected that:

- agricultural productivity in low latitudes, especially in Africa, will drop sharply with 2º of warming or less (measuring temperatures in degrees Celsius above 1980-1999);
- agricultural productivity and economic output will drop everywhere above 3º;
- extinction of species will become significant by 2º of warming, especially for coral reefs and arctic animals, and will become widespread by 4º;
- the threshold for eventual loss of the entire Greenland ice sheet, ultimately causing seven meters of sea-level rise, is a sustained temperature increase of roughly 2º – 4.5º;
- dangerous climate discontinuities, such as disruption of the North Atlantic meridional overturning circulation or the El Nino-Southern Oscillation (ENSO), become more likely as greenhouse gas concentrations increase, but the thresholds cannot yet be estimated;
- regional catastrophes, such as increased intensity of storms and floods, and loss of fresh water from glacial snowmelt, occur at regionally varying temperatures and become steadily worse as temperatures rise.

The Stern Review, based on roughly the same information base (i.e., research available through 2006), concluded that (Stern 2006, Ch. 8 & 11, quote from p. 293):

The uncertainties about impacts make it impossible to quantify exactly where the marginal impacts of climate change will rise more sharply. However, across the current body of evidence, two approximate global turning points appear to exist, at around 2 – 3°C and 4 –5°C above pre-industrial:

At roughly 2 – 3°C above pre-industrial, a significant fraction of species would exceed their adaptive capacity and, therefore, rates of extinction would rise. This level is associated with a sharp decline in crop yields in developing counties (and possibly developed counties) and some of the first major changes in natural systems, such as some tropical forests becoming unsustainable, irreversible melting of the Greenland ice sheet and significant changes to the global carbon cycle (accelerating the accumulation of greenhouse gases).

At around 4 – 5°C above pre-industrial, the risk of major abrupt changes in the climate system would increase markedly. At this level, global food production would be likely to fall significantly (even under optimistic assumptions), as crop yields fell in developed countries.

Based on a comparison of these impact thresholds with the costs of mitigation, Stern recommended a global target of remaining under 450-550 ppm CO_2-equivalent. Anything lower, he suggests, is impossibly expensive. The higher limit implies a 24 percent chance of exceeding a temperature increase of 4^oC and a 7 percent chance of more than 5^o; the lower limit still allows a 3 percent chance of hitting 4^o and a 1 percent chance of 5^o (Stern measured temperatures from the present, implying a starting point 0.1 – 0.2^o higher than the IPCC estimates.) Lower temperature thresholds are much more likely to be breached: at 450 ppm there is a 78 percent chance of hitting 2^o and a 18 percent chance of 3^o; at 550 ppm there is a 99 percent chance of at least 2^o and a 69 percent chance of 3^o (Stern 2006, Box 8.1, p. 195).

In a related journal article, Stern speculated that 5^oC above preindustrial temperatures (or 4.3^o above present temperatures) could imply 10 meters or more of sea-level rise, and said,

"The last time temperature was in the region of 5°C above preindustrial times was in the Eocene period around 35–55 million years ago. Swampy forests covered much of the world and there were alligators near the North Pole." (Stern 2008, p. 6)

In a more recent analysis, Cameron Hepburn and Nicholas Stern suggested that the Review underestimated the risks of catastrophic climate change at $4\text{-}5^oC$ of warming, but still maintained that stabilization below 450 ppm would be unaffordable. Hepburn and Stern thus advocate targets of 450-500 ppm, noting encouraging signs of policy discussion of a 450 ppm target (Hepburn and Stern 2008).

The warnings from climate scientists, meanwhile, continue to grow more and more ominous. IPCC's 2007 report projected only modest sea-level rise, likely to be less than one meter by 2100 – but this was based on excluding the uncertain (but non-zero) contribution of ice-sheet melting. Detailed research by Stefan Rahmstorf, published just after the IPCC deadline for the 2007 assessment, adjusts for estimated ice-sheet melting and suggests almost double the IPCC estimates for sea-level rise (Rahmstorf 2007).

Most recently, a team of ten climate scientists led by James Hansen has published an analysis of paleoclimate data, arguing that the equilibrium response to increased greenhouse gas concentrations is about twice as great as commonly believed; that is, the long-run climate sensitivity (defined as the eventual temperature increase in ^{o}C per doubling of atmospheric CO_2) is 6, not 3 as both IPCC (2007) and Stern assumed. Hansen et al. project that a long-term CO_2 concentration of 450 ppm or greater (equivalent to roughly 475 – 500 ppm CO_2-eq, for comparability with Stern's estimates) would lead to an ice-free Earth and many meters of sea level rise; they advocate a target of 350 ppm CO_2, lower than today's 385 ppm, in order to stabilize ice sheets and major river flows, and reduce climate-caused extinctions. They suggest that reaching this target would require complete elimination of coal use, unless accompanied by carbon capture, by 2030, combined with radically changed forest management practices that sequester increasing amounts of carbon (Hansen *et al.* 2008).

1b. What emissions reductions are best for humanity?

Welfare optimization models attempt to answer the question, what emissions reductions are best for humanity? Other types of IAMs answer this question more obliquely: their results do not offer a policy recommendation but rather can be used to compare scenarios with better or worse outcomes. Regardless of model type, a projection of future emissions based on assumed economic growth rates alone is not enough to arrive at a recommendation of the best course of action. In order to provide counsel to policy makers on the best actions to take for the sake of human welfare, many assumptions are necessary regarding the meaning of well-being and the scale of the threat that climate change poses to well-being.

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, a topic of discussion in Section 3 of this report.)

The extent of uncertainty in the size and pace of climate damages is another important assumption. 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.

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 (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, ρ, plus the product of the elasticity of marginal utility with respect to consumption per capita, η, and the growth rate of income or consumption per capita, $g(t)$.

1) $$r(t) = \rho + \eta g(t)$$

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 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.[4] 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).

[4] The terminology of descriptive and prescriptive approaches was introduced and explained in Arrow et al. (1996).

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 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.

Box 1: Equity and the Elasticity of Marginal Utility

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.[5] 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 $1,000 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).

[5] If the elasticity of the marginal utility of consumption is a constant η, as in equation 1), 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 2006).

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.[6] The ethical issues involved in discounting abatement costs (as modeled in cost minimization models) 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 $1,000 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.

Scientific uncertainty

There are inescapable scientific uncertainties surrounding climate science, for instance in the climate sensitivity parameter (the temperature increase resulting from a doubling of CO_2 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_2-equivalent would lead to a 98th percentile chance of 6ºC 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

[6] 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.

triggered by a geologically-instantaneous temperature change that is significantly larger than what separates us now from past ice ages." (Weitzman 2007, p.716).[7]

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 – Chris Hope's PAGE2002 model (Hope 2006). PAGE2002 includes triangular distributions for 31 uncertain parameters; Hope's standard analysis is based on 1,000 iterations of the model; as in other multivariate Monte Carlo analyses, he uses Latin Hypercube sampling[8] 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).

Box 2: The Curse of Dimensionality

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

[7] In more recent work, Weitzman has suggested that climate science implies even greater risks at the 95th-99th 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.

[8] 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.

warming that results from a doubling of CO_2 in the atmosphere and the release of natural CO_2, 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 1,000 iterations, it is highly unlikely that there are any results for which more than a few parameters are assigned 95th 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 2,000 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.[9]

Several studies have added a Monte Carlo analysis onto some of the other IAMs reviewed here.[10] 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)*

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9 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.

10 For an earlier review of attempts to incorporate uncertainty in IAMs see Scott et al. (1999).

Monte Carlo experiments exist in the literature for several other deterministic models. Kypreos (2008) adds five stochastic parameters to MERGE and runs 2,500 iterations; Peck and Teisberg (1995) add one stochastic parameter to CETA-R with an unreported number of iterations; and Scott and co-authors (1999) add 15 stochastic parameters to MiniCAM with an unreported number of iterations. Webster, Tatang and McRae (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.

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:

2) $D = aT^b$

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 four concerns with damage functions in existing IAMs: the choice of exponents and other parameters for many damage functions are either arbitrary or under-explained; there is an implicit, and troubling, ethical content hidden in some damage functions; 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.[11] The DICE-2007 damage function is assumed to be a quadratic function of temperature change with no damages at 0ºC temperature increase, and damages equal to 1.8 percent of gross world output at 2.5º; this implies, for example, that only 10.2 percent of world output is lost to climate damages at 6º. (Nordhaus 2007a).[12] Numerous subjective judgments, based on fragmentary evidence at best, are incorporated in the point estimate of 1.8 percent damages at 2.5º (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 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 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.

Ethical Content

It is also important to note that point estimates relating temperature change to damage are not without ethical content. For example, point estimates of damages used in DICE-2007 (Nordhaus 2007b) include the health effects of climate change, introduced into the model as years of life

[11] DICE-2007 actually uses a slightly more complicated equation which is equivalent to our equation 2), with the exponent b=2, for small damages.
[12] See Ackerman et al. (2008) for a more detailed critique of the DICE-2007 damage function.

lost, where the value placed today on a life lost depends on the discount rate, the year in which the death occurs, the age of the victim (older victims lose fewer years of life), the average regional life expectancy, and the regional income per capita (Nordhaus and Boyer 2000). Specifically, health costs in DICE-2007 are valued at two years of the regional average income for each year of life lost. Table 2 compares the value in DICE-2007 of deaths in Sub-Saharan Africa and the United States. The death of a 25-year-old in the United States in 2005, for example, is valued at more than 300,000 times that of a 25-year-old in Sub-Saharan Africa in 2255.

Table 2: Discounted Value of Deaths in DICE-2007

A Death in Sub-Saharan Africa				
	Age at death	***1***	***25***	***50***
Year of death	***2005***	$34,880	$27,848	$4,380
	2055	$3,820	$2,906	$431
	2255	$9	$6	$1
A Death in the USA				
	Age at death	***1***	***25***	***50***
Year of death	***2005***	$2,051,173	$1,919,120	$1,525,928
	2055	$231,090	$210,466	$159,213
	2255	$591	$502	$340

Source: Nordhaus (2007a; 2007b); and authors' calculations.

FUND (Tol 1999) also includes a value of lives lost as part of its damage function: "People can die (heat stress, malaria, tropical cyclones), not die (cold stress), or migrate. These effects, like all impacts, are monetized. The value of a statistical life is set at $250,000 plus 175 times the per capita income. The value of emigration is set at three times the per capita income, the value of immigration is set at 40 percent of the per capita income in the host region." (p.135) The ethical implications of these types of assumptions – sadly, quite common in the neo-classical economics literature – are staggering.

In MERGE (Manne and Richels 2004), regions' willingness to pay to avert climate damages depends on their per capita income (an exponential parameter represents a willingness to pay set such that at $25,000 per capita income a region would be willing to pay 1 percent of GDP to avert 2.5ºC): "Although the numerical values are questionable, the general principle seems plausible. All nations might be willing to pay something to avoid climate change, but poor nations cannot afford to pay a great deal in the near future. Their more immediate priorities will be overcoming domestic poverty and disease." (p.8)

That domestic poverty and disease are high priorities for developing countries is indisputable, but it does not follow that valuation based a constrained ability to pay is the way to value damage in a model that is optimizing welfare across economically diverse regions. Purchasing power in the face of competing life or death needs is a morally bankrupt method of ranking damages among regions – just because a region cannot pay to avert damage, or indeed to adapt and thereby prevent damage, or to repair damage after it has occurred, does not mean that the suffering is any less real. Willingness to pay is a notoriously bad way to estimate changes to welfare, especially where resources or damages are unevenly distributed (Ackerman and Heinzerling 2004).

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 ºC – 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 ºC 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.

Portraying gradual climate impacts from small changes in temperature as continuous with catastrophic damages seems problematic. Several climate feedback processes point to the possibility of an abrupt discontinuity in the rate of increase of damages at some uncertain temperature threshold or thresholds. 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-based 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 current 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 more than 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.

Cost-effectiveness analysis

Many IAMs are welfare optimization models that closely resemble the logic of cost-benefit analysis: the sum of the present discounted values of a stream of future costs and benefits is defined as welfare; complex computer algorithms are used to find the solution (how much emissions, how much economic growth) that maximizes this measure of welfare. But cost-benefit analysis of the climate problem, which inescapably involves uncertainty about priceless benefits and irreversible losses over the course of several centuries, leads to unimpressive, incomplete results. It is much simpler to approach the problem in a precautionary manner, focusing on the maximum atmospheric concentration of CO_2 at which unacceptable climate outcomes can be ruled out with a high degree of confidence. This has led to widespread supports for numerical goals such as staying under 450, or with somewhat greater risk 550, parts per million of CO_2 in the atmosphere.

Once goals have been set, then there is an important role for economic analysis in determining the least-cost strategy for reaching the goals – and for adjusting the strategy as conditions, and perhaps even the goals, change in the future. For a complex global problem such as climate change, the answers are far from obvious. This use of economics, known as cost-effectiveness analysis, avoids many of the pitfalls of cost-benefit analysis. It deals exclusively with cost minimization, largely avoiding the problems of assigning prices to priceless values, like ecosystems or human lives; costs are much more likely than benefits to have meaningful monetary prices. Costs of environmental protection tend to occur sooner than benefits, so the problems of discounting across generations are reduced or eliminated. Uncertainty is directly addressed in the choice of a precautionary target. Economics remains central to policy decisions, but its role has changed: rather than drawing up the goal for policy, cost-effectiveness analysis is an essential tool for implementing a blueprint which has already been adopted by political deliberation.

For proponents of cost-benefit analysis, it is common to express climate damages in terms of the "social cost of carbon" (SCC), defined as the increase in damages caused by an additional ton of carbon emissions (Clarkson and Deyes 2002; DEFRA 2007; Stanton and Ackerman 2008). In the cost-benefit framework, the benefits calculation, with all its flaws, seems to allow a precise (but not necessarily accurate) estimate of the SCC. If one accepts the SCC estimate, it can be used for project evaluation, to determine the cost of a particular strategy for carbon reduction. Any project that reduces emissions at a cost lower than the SCC would pass the test, having benefits that exceed its costs. On the other hand, if a project would reduce carbon emissions at a cost greater than the SCC, it can be rejected and the taxpayers can be protected from spending "too much" on preventing climate catastrophe.

A partially analogous measure, the marginal cost of carbon reduction, can be calculated from a cost-effectiveness analysis. In principle, the least-cost strategy for reducing carbon emissions should involve listing all possible carbon-reducing measures, in order of increasing cost per ton of carbon reduction, and then going as far up the list as necessary to reach the target. The cost of the most expensive measure needed to reach the target determines the marginal cost of abatement; any project that reduces emissions at a lower cost per ton of carbon should be implemented, since it should be already included in the least-cost strategy. Thus cost-effectiveness analysis generates a different version of the cost of carbon emissions, based on emission reduction costs rather than damage estimates.

The use of the cost estimates, however, is quite different in the two approaches: in cost-benefit analysis, the social cost of carbon determines the plan, whereas in cost-effectiveness analysis, the plan determines the marginal cost of carbon reduction. The focus on the plan for carbon reduction, rather than the SCC, is appropriate because price incentives alone will never be sufficient to solve the problem. Many carbon reduction measures would be cost effective even at a carbon cost of zero – they are immediately profitable – but have not yet been fully implemented. Many more would be profitable at a cost of carbon below the current estimates of the SCC; these, too, are not automatically adopted once the SCC is announced. Other initiatives, in some cases as simple as providing broader access to information, technology, and financing, will be needed to carry out the full menu of "cost-effective" options.

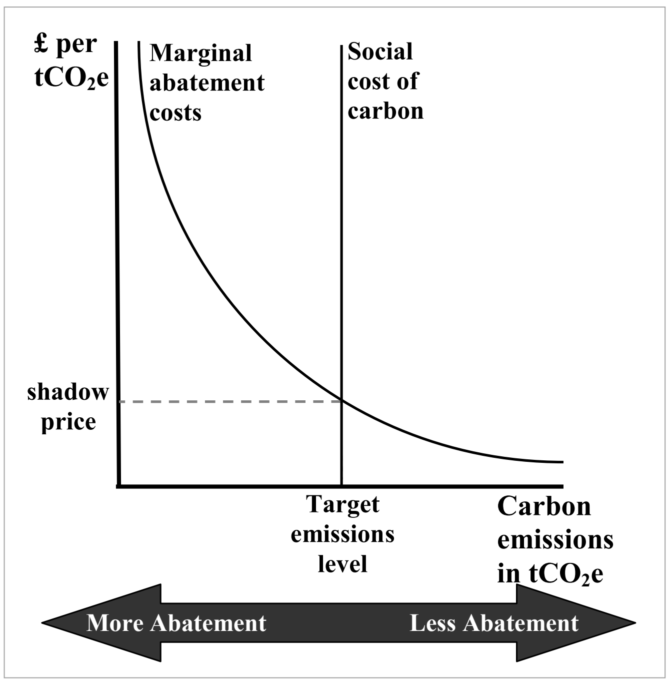
Emission targets, lending themselves to cost-effectiveness analysis, can be set on a precautionary basis. But this is not the only reason to set numerical policy targets prior to economic calculation. The transparency of simple targets may lead to greater public support; it is much easier to explain and adopt a 50 percent, or 70 percent, abatement goal, rather than engage in complex calculations that claim to estimate the optimal level of emissions abatement. In this case it is not the uncertainty and risk of catastrophe that motivates a numerical standard, but rather the importance of promoting public support and participation.

Of the types of climate economics models discussed in this review, cost minimization models are the best suited to cost effectiveness analysis, while welfare optimization most are most closely associated with cost-benefit analysis and the SCC. The latter answer the question of how much global emissions abatement to engage in by searching for a level of emissions will maximize a consumption-based welfare measure. In contrast, cost minimization models begin with a target or threshold temperature, emissions or atmospheric concentration level and then search for the least cost way to achieve this goal.

Box 3: Vertical Damages and Cost Effectiveness

Any firm limit to emissions can be depicted as a vertical social cost function, or a social cost function that has a vertical section. Vertical costs are perfectly inelastic: there is no amount of money that society would accept to increase emissions beyond the stated limit; above the emissions limit, social costs are infinite (see Figure 2). When social costs are perfectly inelastic, any attempt to measure them with the goal of assigning a price to a negative externality (like a charge set on the use of carbon) would be both fruitless and unnecessary: all that matters in this case is an accurate accounting of the marginal abatement cost at the target emissions level. The resulting shadow price can then be used as an incentive, and it should be the "correct" price – the price that will cause the desired amount of abatement. Of course, if the marginal abatement costs have been measured incorrectly, the shadow price will fail to provide the correct incentives.

Figure 2: Vertical Social Cost Curve



Cost effectiveness analysis is a closely related approach that avoids the shadow price method's reliance on price incentives to do the heavy lifting. A cost effective strategy is the most efficient (or cheapest) means to reach a stated goal and is usually implemented through regulation. If the goal is a given amount of carbon abatement, than all possible abatement strategies would be listed along with a schedule of the expected marginal cost of abatement for each project at each possible level of abatement.

2. Where should these emission reductions (and emissions) take place?

Using scientific projections, and economic interpretations of scientific outcomes, policy makers have the information necessary to establish limits for global greenhouse gas emissions in future years. A global emissions budget, however, sheds no light on the question of where in the world these reductions should take place. Greenhouse gases are global or universal pollutants; any unit of emissions from anywhere in the world has the same effect on global concentrations, and it is global concentrations that determine local effects.

Likewise the abatement of one unit of greenhouse gas emissions will have the same effect regardless of its country of origin. To answer the question, where should emissions reductions take place, it is necessary to examine each region's potential for low-cost abatement and its track record in implementing abatement measures. Note that the question of who will pay for abatement is quite separate. To find the most cost-effective abatement solution to the global climate problem, the ability of each country to pay for emissions reduction measures must be treated as distinct from local abatement costs. A low-carbon development path will most likely combine less expensive abatement measures available in developing countries with financing from higher-income countries.

2a. Where is the best potential for low-cost abatement?

There are several well-known technical projections of the cost of abatement over time and across sectors or abatement measures.[13] Marginal abatement cost curves are created by means of a detailed analysis of existing technologies, and the expected development and distribution of new technologies, often by country or region. The best known of these abatement cost projections, the McKinsey costs curves (Enkvist *et al.* 2007), exists outside the bounds of any climate economics model, predicting neither emissions nor damages. Many IAMs use McKinsey or other abatement cost literature to calibrate the pace of technological change and cost of abatement measures.

Modeling technological change over time is one of the most difficult challenges for IAMs. To do it well requires a great level of specificity regarding abatement technologies, rates of development and diffusion, energy generation techniques, fuels and economic sectors, trade in goods and ideas between nations, and flows of investment in research and development. Often, the data requirements for parameters inputs to IAMs overwhelm the existence of reliable data or projections, especially for future time periods. Regionally disaggregated IAMs can only shed light on the question of where abatement measures should take place if they can accurately model endogeneity in technological change.

[13] See especially a series of reports on marginal abatement curves by McKinsey et al. (http://www.mckinsey.com) and the International Energy Agency's projections in the 2008 World Energy Outlook (http://www.iea.org/).

Marginal abatement cost curves

The McKinsey (2007) cost curves plot potential for abatement by cost of abatement measure, in order of marginal cost.[14] According to their projections, abatement sufficient to achieve a 450 ppm CO_2-equivalent stabilization trajectory in 2030 – given business-as-usual growth in emissions – would have a marginal cost of €40 per ton of CO_2-e. This is to say that all of the measures necessary to achieve this level of abatement have per unit costs no higher than €40 per ton of CO_2-e. Nearly one-quarter of the emissions reductions with price-tags of €40 or less have zero or negative costs, primarily energy efficiency improvements. The abatement potential in developing countries amounts to more than half of all abatement measures below €40 per ton of CO_2-e in cost, in part because of their higher rates of economic growth; it is often less expensive to build new low-carbon technology than to reduce emissions from existing facilities and energy systems.

The McKinsey curves do not project how much abatement will happen in the future; only the potential for abatement is calculated. Actual abatement will depend on political will regarding both domestic emissions reductions and investments in abatement measures abroad. Almost 20 percent of all low-cost abatement potential for 2030 comes from China; another 40 percent comes from the rest of the developing world, mostly in reductions to emissions from forestry and agriculture. Funding from richer countries will be essential to realize the potential for abatement in developing countries (Enkvist *et al.* 2007).

Endogenous technological change

The pace of technological growth and the ease with which it spreads between sectors and countries are key determinants of the future price of greenhouse gas abatement. Most IAMS (among those current in the literature) make the attempt to endogenize technological change using methods that vary from very simply assumptions regarding the technological growth over time to elaborate models with many sectors, fuels, abatement technologies, and feedback mechanisms.

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.

[14] The marginal abatement cost is the cost of the next unit of abatement; it is not the same as the average abatement cost. Assuming that abatement measures are pursued in order of cost, from cheapest to most expensive, the marginal cost is the next abatement measure available, having exhausted all less expensive measures, and the average cost is considerably lower than the marginal cost.

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.

Box 4: Understanding Increasing Returns

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 an 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 (Sano *et al.* 2006). 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.

2b. What will a new low-carbon development path look like?

There is a rich strain in recent development literature regarding anecdotal accounts of the potential for mitigation and adaptation measures. Kok et al. (2008) summarizes this literature and advocates for development policies that reduce vulnerability to climate damages and promote low-carbon technologies, but warns that examples of such policies are few and far between.[15] Policies on a national or regional scale are particularly uncommon; Brazil's alcohol fuel program is a frequently cited exception that has generated jobs, improved fuel security and air quality, and lowered greenhouse gas emissions. Potentially successful areas for "climate proofing" development policies include bioenergy crops (with the caveat that there may be negative trade-offs with food production), disaster prevention, energy security, and transport.

Kok et al. (2008) emphasize the need for international financial flows to make climate-friendly development policies viable, and the difficulty of replicating policies from one country or region to another. The need to "mainstream" climate change into international agreements and

[15] See also, Metz and Kok (2008)

institutions is a frequent recommendation found in this literature. Kok et al. compile a range of suggestions for mainstreaming, from using existing provisions in international conventions to drawing on UNEP's Finance Initiative as an insurance mechanism. Finally, they recommend voluntary or mandatory obligations to implement climate-friendly development policies as an alternative way for low-income countries (that would be unduly burdened by direct requirements for emissions reductions) to participate in a global climate agreement.

There have also been several large, multi-country studies of the likely impacts of climate-friendly development policies. The UNEP Risø Center's Development and Climate Project has worked with research institutes in each country studied to assess the potential for policies that simultaneously reduce greenhouse gas emissions and promote social and economic development goals (Halsnæs *et al.* 2008). Risø studies have been conducted in Bangladesh, Brazil, China, India, Senegal, and South Africa. World Resources Institute (WRI) has conducted similar studies in Brazil, China, India, and South Africa in their Growing in the Greenhouse Project (Bradley *et al.* 2005). WRI's focus in these studies is on what they call "Sustainable Development Policies and Measures" or policies that combine domestic development objectives with greenhouse gas reductions. A third study of this nature was conducted by OECD in Bangladesh, Egypt, Fiji, Nepal, Tanzania, and Uruguay (Agrawala 2005). This study focused on both opportunities for and difficulties with mainstreaming climate measures in development planning and assistance.

The potential for developing countries to achieve a low-carbon development pathway will depend in part on the outcome of international climate negotiations and the willingness of richer countries to fund abatement, adaptation and economic development measures outside of their own borders. A second strain of recent development literature focuses on equity issues in international climate agreements and the climate negotiation process itself (Grasso 2007; Richards 2003; Roberts 2001). Martin Khor (writing primarily in reports and policy briefs of the Third World Network) is, perhaps, one of the best-known advocates for the primacy of equity concerns in international climate negotiations (Khor 2007a, b, 2008a, b). Khor calls attention to the need to integrate climate concerns with development issues and the principles of equity, historical responsibility, and common but differentiated responsibilities set out in the Kyoto Protocol. He has also written extensively on the challenges of technology transfer, including financing and intellectual properties rights.

3. Who should pay for emissions reductions and adaptation measures?

After establishing a scale of and timetable for global emissions reductions and the countries in which these reductions would be most efficient, a third key question for climate and development policy is, who should pay for emissions reductions and adaptation measures? Our first two questions can be a matter for science and technology while this third question – who will pay – is clearly a matter of ethics. If the physical location of abatement and adaptation can be successfully alienated from the responsibility to pay for these measures, than we can approach this question purely on ethical grounds.

One way to imagine this separation – either as a practical mechanism or a rhetorical device – is to posit a global fund which pays for all abatement measures everywhere in the world. Choices about which measures to fund are made purely on scientific and technical grounds. The choice of who pays in to this global fund (often referred to as "burden-sharing" in the literature) is a matter of ethics: What countries or individuals bear more or less responsibility for the problem of climate change? Who can best afford to contribute without compromising the basic standard of living required by human rights?

IAMs often include implicit assumptions regarding ethical choices. Some of these assumptions have been well-examined in the literature, the discount rate, for example. Other assumptions are relatively unknown, like the welfare weighting system common to many welfare optimization models. In 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, many IAMs employ Negishi welfare weights, 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.

3a. What is the equitable division of emissions rights?

Numerous burden sharing mechanisms have been introduced both in the climate and development literature, and in the global climate negotiation process. Several of these focus purely on the division of emissions rights among countries, assuming (implicitly or explicitly) that every country pays for its own emissions abatement with the exception of generating revenue by selling emissions rights. A few of the most common proposals include:

Equal per capita emissions rights: Every person has an equal right to the global sink for greenhouse gases. A limit is set on world annual emissions. This limit is divided by world population to arrive at an equal per capita right to emit. Each country is allocated a level of emissions calculated by multiplying the per capita emission right by the country's population.

The limit on global emissions would be reduced overtime to achieve a desired stabilization trajectory (Agarwal and Narain 1991; Narain and Riddle 2007).

"The Indian Proposal": Developing countries will observe a cap on per capita emissions set by average Annex I per capita emissions. As industrialized countries reduce emissions, the cap on developing countries' emissions will likewise shrink. The plan was proposed by Indian Prime Minister Manmohan Singh in general terms at the 2007 G8 meeting in Germany and in greater detail in his release of India's National Action Plan on Climate Change in June 2008 (Singh 2008).

Individual Targets: This approach assigns equal emissions rights (or a "universal cap") to individuals in order to meet a desired stabilization trajectory. Each nation's emissions allocation its sum of actual individual emissions, for all residents with emissions less than the cap, and target individual emissions, for all residents with emission equal to or more than the cap. In this way, high emitters in a low emissions country do not free ride by de facto absorption of low emitters unused rights (Chakravarty *et al.* 2008).

Contraction and convergence: This plan combines equal rights to emit with grandfathering (or rights based on past emissions – the higher the past emissions, the larger the grandfathered emissions rights). Each country is allocated emission rights based on its past emissions. Countries that exceed desired per capita global emissions have their allocation reduced in each succeeding year while countries that emit less than this target receive a higher allocation each year. Over time, global emissions contract while high and low emitting countries converge on the same target per capita emissions (GCI 2008).

One Standard, Two Convergences:

Each country is allocated a right to a total contribution to greenhouse gas concentrations based on equal per capita cumulative allowances targeted to meet a desired stabilization trajectory. Differentiated annual emissions ceilings for industrialized and developing countries are adjusted each year to achieve convergence. A relatively high (in comparison to current emissions) ceiling for developing country emission allows these countries to increase their annual emissions to achieve economic growth before having to decrease emissions to stay within their cumulative cap. Trading of emissions rights makes it possible for all developing countries to use their entire allowance (Gao 2007).

A few burden-sharing plans eschew the assumption that each country must pay for its own abatement and include a more explicit discussion of who pays for abatement where:

Greenhouse Development Rights: The burden of emissions reductions is shared among countries according to their capacity to pay for reductions and their responsibility for past and current emissions. Each of these criteria is defined with respect to a development threshold so as to explicitly safeguard the right of low-income countries to economic growth; only individuals with incomes above this threshold have a responsibility to pay for emissions abatement. Each country is assigned an emissions allocation based on per capita rights. In addition, each country is assigned an obligation to pay for abatement – whether at home or abroad – based on their share of cumulative emissions since a base year (such as 1990) and the cumulative income of their population with incomes above the development threshold (Baer *et al.* 2007).

Revised Greenhouse Development Rights: Proposed a team of researchers at Tsinghua University for a report for the Chinese Economists 50 Forum, the Revised Greenhouse Development Rights builds on Baer et al. (2007)) by including cumulative emissions back to 1850, and accounting for emissions based on consumption (rather than production) within each country. The result is a greater responsibility on the part of industrialized countries to pay for emissions reductions around the world (Fan *et al.* 2008).

3b. Why does economic analysis often overlook issues of equity?

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 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 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.

In the words of three leading modelers:

> ***For RICE:*** *Under the utilitarian weights, regions have different shadow prices of capitals. The social planner can improve the global welfare by moving capitals from low price places to high price places. OHI [Other High Income] is the region with the lowest shadow price of capital. However, there are no conventional capital flow channels in our setting. The capital from OHI "inundates" the small scale inter-connections of technological transfers. Such flows are redistributions under the pretext of technological transfers. Our simulation here actually explains why some other modelers' results on financial transfers are unreasonably high…Furthermore, we show that reasonable and correct magnitude and directions of technological transfers can only be modeled by using the Negishi social welfare weights. (Yang and Nordhaus 2006, p.738, 731)*

> ***For MERGE:*** *A fixed set of Negishi weights defines a so-called Negishi welfare problem, the solving of which corresponds to the maximizing of the global welfare function. MERGE updates iteratively the Negishi weights in solving sequentially the corresponding Negishi welfare problems. The steps to update the Negishi weights are performed until a pareto-optimal equilibrium solution is found. (Kypreos 2005, p.2723)*

> ***For CETA:*** *To determine the competitive equilibrium in CETA-M, we use an approach employing Negishi weights…When this problem is solved for any arbitrary set of weights, the shadow prices of the constraints requiring net imports to sum to zero are the international prices for the corresponding goods. These prices may then be used to calculate a present value trade surplus or deficit for each of the two regions for this model solution. The competitive equilibrium is then found by adjusting the Negishi weights until the present value trade surplus (or deficit) is zero. (Peck and Teisberg 1997, p.4)*

Box 5: Negishi Welfare Weights

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.

Modelers who have described the necessity of adding Negishi weights to regional welfare optimization models as a mere technical fix have obscured a fundamental issue of equity. The Negishi problem might more accurately be described in the language of a seminal juncture in the evolution of modern neo-classical economic thought, the "marginal revolution." Early in the development of neo-classical theory, it was recognized that the principle of diminishing marginal utility of income, combined with a Utilitarian social welfare function that is an unweighted sum of the welfare of individuals, would imply that a redistribution of income from the rich to the poor always results in an increase to social welfare. Many economists were not prepared to accept this radically redistributive conclusion from their theory. Innovations that eliminated the argument for equalization included the assumption that the welfare of different individuals cannot be directly compared (or therefore, summed in the classic utilitarian manner), and that the welfare implications of public policies should be judged instead by the new principle of Pareto optimality.

Instead of a Utilitarian welfare function that sums up individual welfare, Pareto optimality judges social welfare on these grounds: an improvement to welfare has occurred if someone has been made better off without making anyone else worse off. Cost-benefit analysis is a practical application of Pareto optimality with one simple addition – if those that gain from an action could in principle compensate those that lose and still have a little something left over for themselves, than the action is said to result in a gain to welfare, even if no such compensation actually takes place.

The connection between Negishi weights and Pareto optimality becomes easier to identify when the condition of equalizing the marginal product of capital is replaced with the mathematically equivalent condition of equalizing the marginal utility of income across regions. The marginal product of capital is too high in regions with low capital (i.e. low-income regions), so the Negishi process lowers their weights and acts as if they are less important. Conversely, the marginal product of capital is too low in high-income regions with abundant capital; the Negishi weights increase the importance of the welfare of such regions. In simple models of the economy, per capita income is proportional to the capital-labor ratio, and it follows that Negishi weights cause the model to behave as if every region had the same income per capita,[16] a point that several modelers, somewhat cynically, acknowledge:

> *The Negishi weights are an instrument to account for regional disparities in economic development. They equalize the marginal utility of consumption in each region for each period in order to prevent large capital flows between regions. …although …such capital flows would greatly improve social welfare, without the Negishi weights the problem of climate change would be drowned by the vastly larger problem of underdevelopment." (Keller et al. 2003, p.7)*

> *We do this not as a brief for the existing international distribution of resources and income but because it is the starting point for analyzing potential improvements in economic welfare that would arise from policies that are imposed on the actual world economy. (Nordhaus and Yang 1996, p.746)*

> *In order to apply this approach, Negishi weights must be determined for each of the regions. These are chosen so that each region's outlays do not exceed the value of its wealth. In equilibrium, the weight must equal each region's share of the world's wealth…The Negishi weights may be interpreted as each region's dollar voting rights in the allocation of the world's resources. (Manne 1999, p.393, 394)*

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.[17] In a recent assessment of the Stern Review, Partha Dasgupta (2007) argues on equity grounds that the PAGE2002 model has an insufficient elasticity of the marginal utility of consumption (recall that

[16] In a simple (Cobb-Douglas) two-region, one-period model, the ratio of the Negishi weights is the ratio of the capital-labor ratios raised to a fixed power.
[17] 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).

PAGE uses $\eta=1$) – or too little emphasis on interregional equity; Dasgupta advocates an η, 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).

Negishi weights lead to a Pareto optimal result, but the ethical implications of Pareto optimality are by no means above reproach.[18] 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.

[18] See Chapter 2 in Ackerman and Heinzerling (2004) for a more complete discussion.

4. In the absence of climate policy, what is likely to happen?

The basic outline of all climate policy – what should be done to slow or even halt climate change – depends on these first three questions:

- How much emissions reductions should take place by when?
- Where should these emission reductions (and emissions) take place?
- Who should pay for emissions reductions and adaptation measures?

A further, counterfactual question is helpful to our understanding of the consequences of failing to implement the policy so formed: In the absence of climate policy, what is likely to happen?

Emissions scenarios, like those established by the IPCC, project what will happen to the climate given an assumed rate of economic growth. Many IAMs tell the opposite side of this story: What will happen to the economy given an assumed rate of emissions growth. In some models this is a one way relationship; other models attempt to represent the feedback processes between climate and economy.

4a. What will happen to the climate given assumed economic growth?

Many of the integrated assessment models reviewed in this report take as a starting point the IPCC emission, population, and economic growth scenarios, or otherwise use these scenarios to calibrate projected emissions. This section explains these scenarios in detail.

IPCC emissions projections belong to four scenario families, characterized by the "storylines" excerpted in Box 6:

Box 6: IPCC Scenario Families

The **A1 storyline** and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The

A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system.

The **A2 storyline** and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The **B1 storyline** and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The **B2 storyline** and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Source: Excerpted from Nakicenovic et al. (2000, Section 4.2.1)

The IPCC's four scenario families, and their 40 more-specific scenarios, have remained unchanged since the IPCC's *Third Assessment Report* (2001). These scenario families differ from one another in terms of their projected population and economic growth rates, and the speed with which incomes in industrialized and developing countries converge. The A1 and B1 scenario families share the lowest population projections, 7 billion in 2100; B2 projects 10 billion and A2, 15 billion. This population range, 7 to 15 billion in 2100, is now somewhat out of date. The most recent population projections released by IIASA and UNDESA revise this range to 6 to 11 billion in 2100 (see Table 3; see also Appendix A for more complete data regarding current IIASA and UNDESA projections) (Nakicenovic *et al.* 2000; Schenk and Lensink 2007).

Table 3: IPCC 2007 Scenario Families, Population Projections

IPCC Scenario Families (Nakicenovic et al. 2000)	Total population (billions)		
	2050	**2100**	**Source**
Data used in current scenarios (2100 as cited in Nakicenovic et al. 2000; 2050 from original sources)			
A1	8.5	7	Lutz (1996) low fertility rate, low mortatility
B1	8.5	7	Lutz (1996) low fertility rate, low mortatility
B2	9.4	10	UN (1998) medium variant
A2	11.3	15	Lutz (1996) high fertility rate, high mortatility
Data from updated sources (for purposes of comparison)			
A1	7.8	6.2	Lutz et al. (2008) 10th percentile
B1	7.8	6.2	Lutz et al. (2008) 10th percentile
B2	8.9	9.1	UNDESA (2004) medium variant
A2	9.9	11.1	Lutz et al. (2008) 90th percentile

Source: Nakicenovic et al. (2000); Lutz (1996); Lutz et al. (2008); UNDESA (2004).

Scenario families B2 and A2 share the lowest economic growth, reaching $374 trillion[19] by 2100 with an average 2.2 percent annual growth over the 21st century (see Table 4).[20] Scenario family B1 has slightly higher long-range economic growth reaching $523 trillion by 2100 at 2.5 percent annual growth, and A1 has the fastest growth reaching $822 trillion at 2.9 percent annual growth. In terms of per capita GDP, the gaps from scenario to scenario are wide: the world average for the A1 scenario families is $122,000 in 2100; B1 is $70,000; B2 is $34,000; and A2 is $24,000 (see Table 5).

[19] In this section, all money values are given in 2005 U.S. dollars, except where otherwise noted.

[20] Note in Table 4 that the growth rates for B2 and A2 differ slightly. Scenarios families are designed to meet a target world GDP in 2100; for B2 and A2 this is $250 in 1990 U.S. dollars. The specific scenarios within these scenario families have average annual growth rates over the period 1990 to 2100 that range from 2.0 to 2.3 percent. The long-term growth rates reported in Table 4 are the median rates for all scenarios in that family.

Table 4: IPCC 2007 Scenario Families, GDP and GDP Growth Rates

IPCC Scenario Families (Nakicenovic et al. 2000, in 2005 U.S. dollars)					
			1990-2100		
Region	**1950-1990**	**A1**	**B1**	**B2**	**A2**
World GDP (trillions)		$822	$523	$374	$374
Annual GDP growth rates					
OECD90	3.9	1.8	1.5	1.1	1.6
REF	4.8	3.1	2.7	2.3	2.5
IND	3.9	2.0	1.6	1.3	1.7
ASIA	6.4	4.5	3.9	3.8	3.3
ALM	4.0	4.1	3.7	3.2	3.2
DEV	4.8	4.3	3.8	3.5	3.3
WORLD	**4.0**	**2.9**	**2.5**	**2.2**	**2.3**

Note: OECD90 is OECD countries in 1990; REF is Former Soviet and Eastern European transition countries; IND is the industrialized countries, or OECD90 and REF; ASIA is all Asia, excluding any Middle Eastern countries; ALM is all other countries not included in OECD90, REF and ASIA; DEV is the developing countries, or ASIA and ALM.
Note: Original values in 1990 U.S. dollars; adjusted for inflation using the Consumer Price Index (CPI-U): 195.3/130.7.

Source: Nakicenovic et al. (2000); BLS (2008).

Table 5: IPCC 2007 Scenario Families, GDP Per Capita

IPCC Scenario Families (Nakicenovic et al. 2000, in 2005 U.S. dollars)					
GDP per capita					
			2100		
Region	**1990**	**A1**	**B1**	**B2**	**A2**
OECD90	$26,600-30,800	$163,000	$120,000	$91,000	$88,000
REF	$3,300-4,000	$151,000	$78,000	$57,000	$30,000
IND	$19,100-21,500	$160,000	$109,000	$81,000	$69,000
ASIA	$600-900	$108,000	$54,000	$30,000	$12,000
ALM	$1,900-3,100	$91,000	$67,000	$24,000	$22,000
DEV	$1,000-1,600	$100,000	$60,000	$27,000	$16,000
WORLD	**$5,500-6,000**	**$112,000**	**$70,000**	**$34,000**	**$24,000**

Note: OECD90 is OECD countries in 1990; REF is Former Soviet and Eastern European transition countries; IND is the industrialized countries, or OECD90 and REF; ASIA is all Asia, excluding any Middle Eastern countries; ALM is all other countries not included in OECD90, REF and ASIA; DEV is the developing countries, or ASIA and ALM.
Note: Original values in 1990 U.S. dollars; adjusted for inflation using the Consumer Price Index (CPI-U): 195.3/130.7.

Source: Nakicenovic et al. (2000); BLS (2008).

The other key difference among scenario families is the rate of convergence between the incomes of industrialized and developing countries. The scenarios follow two main classes of markers (summarized in Table 6): the year in which developing countries' level of GDP, GDP per capita or emissions reaches that of industrialized countries in 1990; and the year in which developing countries match industrialized countries in terms GDP, GDP per capita or emissions. The A1 and B1 scenario families have the fastest convergence rates, while A2 has the slowest. In no IPCC scenario does developing countries' average GDP per capita (in MER terms) catch up with that of industrialized countries by 2100.[21]

Table 6: IPCC 2007 Scenario Families, Convergence Dates

IPCC Scenario Families (Nakicenovic et al. 2000, in 2005 U.S. dollars) Date when developing regions reach 1990 levels in industrialized regions or overtake current year (2005) levels				
Reaching 1990 IND levels	**A2**	**B2**	**A1B**	**B1**
GDP (MER)	~ 2030	~2020	~2015	~2020
GDP (PPP)	~ 2010	~2005	~2000	~2000
GDP (MER) per capita	>2100	~2080	~2050	~2060
Overtaking IND	**A2**	**B2**	**A1B**	**B1**
GDP (MER)	~2060	~2035	~2030	~2035
GDP (PPP)	~2030	~2020	~2015	~2010
GDP (MER) per capita	-	-	-	-

Source: Nakicenovic et al. (2000).

4b. What will happen to the economy given assumed future emissions?

Scenario-based models, like the PAGE model used in the Stern Review, project the economic impacts of an assumed emissions scenario. Optimization models attempt to represent the circular relationship between emissions and economic growth by including feedback mechanism, usually equations representing abatement costs and damage costs. General equilibrium models, common in macro-economic analysis, have many technical problems that require the introductions of assumptions not at all consistent with even the most basic representation of endogenous technological change.

Scenario-based models (e.g. PAGE and the Stern Review)

The PAGE2002 model, used in the Stern Review (2006), is designed to match the IPCC's A2 scenario family in terms of population growth and greenhouse gas emissions through 2100 (Hope 2006). Gross GDP levels by regions for PAGE are reported in Table 7. The long-term economic growth rate used in PAGE is 2.6 percent annual growth, compared to 2.3 percent in the IPCC's A2 scenario; in PAGE, world GDP levels are $629 trillion in 2100, nearly twice that of the A2 scenario, and GDP per capita is approximately $37,000, compared to $24,000 for A2. PAGE continues its projections out to 2200 with world GDP reaching $6,300 trillion. (Note that PAGE is a scenario-based model. There is no feedback mechanism connecting economic growth, economic damages, and emissions levels.)

[21] In the IPCC scenarios, economic differences among regions are expressed in terms of market exchange rates (MER) with no adjustment for purchasing power parity (PPP).

Table 7: PAGE 2002: GDP and GDP Growth Rates

PAGE 2002 (Hope 2006; in 2005 U.S. dollars in PPP terms)				
GDP (trillions)	**2060**	**2100**	**2200**	**annual growth 2000-2100**
European Union	$24	$47	$252	1.6%
Former USSR; Eastern Europe	$18	$51	$669	2.9%
USA	$27	$51	$277	1.6%
China and centrally planned Asia	$51	$145	$1,718	3.3%
India and South-East Asia	$43	$121	$1,431	3.3%
Africa and the Middle East	$30	$83	$809	3.2%
Latin America	$35	$95	$922	3.2%
Other OECD	$18	$35	$189	1.6%
World Total	**$246**	**$629**	**$6,266**	**2.6%**
Note: Original values in 2000 U.S. dollars; adjusted for inflation using the Consumer Price Index (CPI-U): 195.3/174.0.				

Source: Hope (2006); BLS (2008); GDP levels and world GDP growth rate are authors' calculation based on results reported in Hope (2006).

Welfare optimization models

The DICE-2007 model is a welfare optimization model: there is feedback between economic growth , economic damages and emissions, but population is determined exogenously; world population is set to approach 8.5 billion asymptotically, nearing this level in 2100 (see Table 8) (Nordhaus 2007a, 2008).

Table 8: DICE-2007, Population, GDP and GDP Growth Rates

DICE-2007 Results (Nordhous 2007 and authors' caculations from DICE-2007 model; in 2005 U.S. dollars in PPP terms)				
	2055	**2105**	**2205**	**annual growth 2005-2105**
Population (billions)	8.2	8.5	8.6	
Optimal case				
Gross output (trillions)	$140	$277	$916	5.5%
Per capita gross output	$17,000	$32,400	$106,600	10.6%
Net output (trillions)	$138	$270	$874	5.5%
Per capita net output	$16,800	$31,700	$101,700	10.6%
Business-as-usual (Base 250 years) case				
Gross output (trillions)	$140	$276	$901	5.5%
Per capita gross output	$17,000	$32,300	$104,800	10.6%
Net output (trillions)	$138	$268	$832	5.5%
Per capita net output	$16,800	$31,400	$96,700	10.6%
Percentage difference between optimal and business-as-usual cases				
Gross output (trillions)	0.09%	0.31%	1.68%	
Net output (trillions)	0.16%	0.86%	4.86%	

Source: Nordhaus (2007a; 2008); author's calculation based on DICE-2007 model results.

In DICE growth rates depend on several factors: the exogenous labor force and total factor productivity growth, a discount rate determined by the modeler, climate change damages and abatement costs, and the choice of investment and emissions control rates determined by the optimizing software to maximize the present value of welfare (a concave function of per capita consumption). These factors combine to result in a much higher annual GDP growth rate over the next century: 5.5 percent for DICE-2007, compared to 2.2 to 2.9 for the four IPCC scenario families, and 2.6 for PAGE2002. Average annual GDP per capita growth rates for the 21st century are 10.6 in DICE, very similar to the A1 per capita long-term growth rates, the IPCC scenario with the fastest economic growth and the slowest population growth.

Table 8 above reports both gross and net output (or world GDP) and per capita output for two DICE-2007 scenarios: the optimal scenario, in which the DICE optimizer takes climate damage and abatement costs into consideration as it makes choices about abatement with the goal of maximizing global welfare; and a business-as-usual scenario, in which climate damages occur but the model's optimizer is overridden, forcing it to make the abatement decisions that it would have made if no damages were occurring. Note how little difference there is between these scenarios in 2105: DICE assumes that even fairly large changes in the global annual average temperature (3.2°C in 2105 in the business-as-usual scenario) cause very small economic damages (2.8 percent of world gross output). Differences between the optimal and business-as-usual scenarios become more appreciable by 2205, when the change in the annual average temperature has reached 5.4°C.

Further sensitivity analysis of the DICE-2007 revealed that the model returns a rosy view of the world economy in almost any circumstances. It would be necessary for the global average annual temperature to rise by 19^{o}C, for example, for DICE's net output to be reduced by one-half. Indeed, DICE is constrained to be optimistic by limits set on its parameters: temperature may rise no higher than 10^{o}C, even in the business-as-usual scenario, and global consumption can drop no further than $20 trillion (implying a floor of $3,100 per capita in 2005 or $2,300 per capita in 2205 because of population growth). DICE's production function makes rapid economic growth an imperative: both total labor productivity and the size of the labor force grow exogenously, without regard to the economic and social damages of climate change. Damages in DICE-2007, impact only on the current year's income; depreciation alone decreases the capital stock. In the optimal case, if emissions were to damage DICE's economic growth, 100 percent abatement is immediately available for about 5 percent of world output, but even in the business-as-usual case, emissions remain low and economic growth high well into the 22nd century.[22]

[22] Our Monte Carlo analysis of DICE-2007 is summarized in Ackerman et al. (2008)

CGE models

Computable general equilibrium (CGE) models are widely used for modeling international trade and development, as well as climate policy. They incorporate interactions among all sectors of the economy, not just the ones of immediate interest; they reflect supply and demand balances, and resource and budget constraints, in all markets simultaneously. Their name suggests a link to one of the most imposingly abstract branches of economics, general equilibrium theory, although in practice applied modelers do not use much of the theory beyond the idea that all markets clear at once (on the limitations of the theory, especially for dynamic analysis, see Ackerman (2002)).

The comprehensiveness of coverage of the economy is the good news about CGE models: they offer a systematic framework for analyzing price and quantity interactions in all markets, ensuring that both direct and indirect effects are counted, while none are double counted. The bad news about the models also stems from their comprehensiveness: in order to provide such complete coverage of the economy, they rely on debatable theoretical simplifications, and impose enormous information requirements (Ackerman and Gallagher 2004, 2008).

Any modeling exercise involves simplification of reality. The question is not whether simplifications are involved, but whether those simplifications clarify or distort the underlying reality. Unfortunately, CGE model structures and assumptions introduce major, unintended distortions into the results. In order to ensure that, as prescribed by economic theory, all markets always clear, CGE models apply an artificial, unrealistic procedure for modeling international trade, and eliminate unemployment and "no-regrets" emission reductions by arbitrary fiat.

Box 7: Armington Elasticities

Following a procedure developed by Paul Armington (1969), global CGE models estimate international trade flows by using a set of elasticities to apportion a country's demand for a specific good (such as U.S. demand for paper) between domestic production and imports, and then to distribute the demand for imports among countries that export that good. Although mathematically convenient, this procedure imposes a number of implausible assumptions on the model; for instance, regardless of price changes, no country ever shifts completely from importing to exporting a commodity, or vice versa (Tokarick 2005). While considerable research effort has gone into estimation of Armington elasticities, substantial uncertainties and hence wide confidence intervals remain in the latest estimates (Hertel *et al.* 2004). Such questions have proved to be of more than academic importance; rival analyses of a proposed free-trade agreement between the United States and Australia came to opposite conclusions about whether or not it would be beneficial for Australia, based largely on their use of different Armington elasticities (ACIL Consulting 2003; Centre for International Economics 2003).

For policymakers, one of the most important results of economic models is the forecast of employment impacts. Much of the political passion surrounding climate policy reflects the hopes and fears about its effects on employment. Will new energy conservation and efficiency investments create jobs? Or will the high costs of these investments depress incomes and spending, and eliminate jobs in carbon-intensive industries? Most CGE models are silent by design on these fundamental, controversial questions. This issue is highlighted in a literature review by Joseph Stiglitz and Ed Charlton, who write that a standard CGE analysis "... is predicated on a set of assumptions that is not satisfied in most developing countries: full employment, perfect competition, and perfect capital and risk markets" (Stiglitz and Charlton 2004, p. 7). They list a series of problems with CGE models, including the failure to account for the presence of persistent unemployment in developing countries, and the failure to incorporate costs of transition, implementation, and adjustment to policy changes – costs which are likely to be larger in developing countries.

The general problem is that a fixed-employment model does not allow analysis of changes in employment. Each country's aggregate level of employment after a policy innovation is, by assumption, the same as the level before. Workers can and will change industries, but they are playing musical chairs with exactly enough chairs for everyone who had a seat before the music started.

Although the fixed employment assumption is conventional, it is not required for CGE modeling. A number of articles have explored both the possibility and the desirability of calculating employment impacts in a CGE framework (Ganuza *et al.* 2005; Kurzweil 2002; Oslington 2005). A few studies have developed CGE models under the assumption that the employment of unskilled labor in developing countries can vary as needed, while wages remain fixed (Fernández de Córdoba and Vanzetti 2005; Polaski 2006). This is not yet a fully realistic model of labor markets – total employment is still fixed in developed countries, and in skilled labor everywhere – but it is a step in the right direction.

The same logic of perfectly functioning markets has crucial implications for climate policy in another area: "no-regrets" options, i.e. opportunities to reduce emissions at zero or negative net cost, are assumed to be impossible. As the saying goes, there are no $20 bills on the sidewalk, because someone would have picked them up by now. If no-regrets options exist, then the world is not Pareto-optimal: someone could adopt the no-cost or negative-cost opportunities for emission reductions and achieve private gains without cost to anyone else, constituting a Pareto improvement. The standard CGE approach assumes that the world is Pareto-optimal and thus there cannot be any no-regrets options; this raises the overall cost of mitigation compared to an analysis that acknowledges and measures no-regrets options.

Just as a few CGE modelers have begun to experiment with variable-employment models, it should in theory be possible to construct CGE models that relax the assumption of Pareto optimality and allow for no-regrets options for emission reduction. We are not aware, though, of any actual attempts to do so.

Conclusions and policy recommendations

Climate and development are inextricably linked. Successful climate negotiations must acknowledge the interconnections of climate and development, both in policy and in the research efforts that support policy proposals and decision-making processes. Climate negotiations that begin with the assumption that all countries are equally responsible for carrying out and paying for abatement measures ignore two important equity concerns: culpability for the build-up of greenhouse gases in our atmosphere, and differential abilities to pay for climate solutions. Current day inequalities of income and wealth between countries are in part the result of a history of lucrative – but polluting – industrial development. The conflation of the issues of how much abatement is necessary with where it will take place, and of the location of abatement and adaptation measures with a local responsibility to pay for those measures tends to disguise the links between climate and development.

This background paper treats these questions as independent, and reviews the climate and development literature most relevant to address each of four issues:

How much emissions reductions should take place by when? The maximum level of global emissions allowable in each time period is a question for science; thresholds to avoid disaster are well-known and the most recent research supports these findings but suggests that the thresholds of temperature and concentration may be even lower than previously thought. Welfare optimizing models and other IAMs reinterpret these scientific results through the lens of economics, and often find that the costs of slowing climate change are unjustifiably high in the short run and recommend waiting for lower cost abatement options to be developed. Conclusions like this are the product of the faulty assumptions on which these economic models are built: high discount rates, inappropriate or underdeveloped analysis of uncertainty, and arbitrarily optimistic damages projections. Cost effectiveness analysis is an alternate form of economic analysis that begins by taking the thresholds of climate science as a given and then searches for the least cost way to stay below those thresholds. Ethical judgments that are implicit, but difficult to discern, in welfare optimization models, are explicit policy choices in cost effectiveness analysis.

Where should these emission reductions (and emissions) take place? Detailed engineering assessments of potential for abatement by sector and by country offer the best existing advice for policy makers on where to focus abatement measures. The climate economics modeling literature is in a period of rapid development in the representation of endogeneity and path dependence in technological change. Some of models that have made the most successful advances in this regard are cost minimization models, which closely resemble a cost effectiveness analysis. These models are a great advance over earlier models in which technology grew automatically simply with the passage of time, however, high levels of specificity to parameter values for future years likely hampers accuracy in existing cost minimization models.

Who should pay for emissions reductions and adaptation measures? The questions of how much abatement to engage in, and when and where to engage in it, can be answered by science and technology, along with cost effectiveness as a decision-making principle. The question of who should pay for these abatement measures, and for the adaptation measures made necessary by climate damages, cannot be answered by science or by economics. This is an ethical question: Who *should* pay? Many burden sharing plans make the implicit assumption that each country must pay for its own climate measures. More complex burden sharing plans, like the Greenhouse Development Rights scheme, consider a full range of ethical issues and allocate emission rights separate from the responsibility to pay for abatement. In contrast, climate economics models often obscure these issues by presenting results as if they were value-free, when in fact they frequently include a set of hidden assumptions that give disproportional weight to the welfare in industrialized countries.

In the absence of climate policy, what is likely to happen? 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 economic development.

Climate economics models 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.

Climate policy, and the modeling efforts that support it, must take development seriously. Neither science nor economic models can answer ethical questions. A fair allocation of emission rights and responsibility to pay for abatement and adaptation can only be established in a fair and open negotiation process. The question of what is fair has the potential to effectively hobble climate policy. To date most greenhouse gas emissions have come from the developing world but the two or three developing countries with enormous economic growth, industrial development and a rapidly expanding consumer class are enough to change the existing pattern of emissions very quickly. Developing countries must participate for successful global abatement, but developing countries will not sign on to an egregiously inequitable climate deal.

Development policy must take climate seriously because climate damages and/or prohibitive adaptation costs could swamp developing economies; and because as climate damages mount and emissions from the developing world grow, industrialized countries will become increasingly insistent that developing economies keep emissions low. There is no point in fighting for the right to a form of development that hastens the arrival of a world-threatening catastrophe; the only hope for rich and poor countries alike is the creation of a radically new, low-carbon path to economic development.

Some of the studies reviewed here suggest new directions that will be essential in the reconciliation of climate and development goals; others, to varying degrees, overlook or mistake the relationship between these two broad objectives. There is a continuing need for economic research that spells out, in more detail, the connection between protection of the earth's climate and meeting the basic needs of all the world's population.

Appendix A: Population Projections

Table 9: Lutz et al. (2008) IIASA's 2007 Probabilistic World Population Projections

	Total population (billions)	
	2050	**2100**
10th percentile	7.8	6.2
Median	8.8	8.4
90th percentile	9.9	11.1

Table 10: UN (2007) World Population Projections: The 2006 Revision Population Database

	Total population (billions)	
	2050	**2100**
Low variant	7.8	na
Medium variant	9.2	na
High variant	10.8	na
Constant-fertility variant	11.9	na

Table 11: UNDESA (2004) World Population to 2300

	Total population (billions)	
	2050	**2100**
Low variant	7.4	5.5
Medium variant	8.9	9.1
High variant	10.6	14.0

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