Climate and development economics: Balancing science, politics and equity

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Abstract

The interaction of climate and development threatens to create a paradox: economic development could accelerate climate change, which in turn could block further development, locking the world into existing patterns of inequality as the natural environment deteriorates. The solution to this paradox is far from obvious. What analytical tools are needed to chart a path that leads toward sustainable, low-carbon economic development? This article reviews the implications for climate policy of the climate economics and development literature, focusing on three key areas of judgments and assumptions that are built into a number of leading climate-economics models: 1) the treatment of climate science, risk, and uncertainty in climate-economics models; 2) questions of abatement technologies and costs, including a focus on the cost effectiveness method of economic analysis; and 3) ethical issues surrounding the distribution of the costs of emission reductions and adaptation measures. The article concludes that since climate and development goals are inextricably linked, there is a need for a new economic analysis that can help interpret and guide the creation of an innovative, low-carbon path to economic development.

Keywords: Climate economics; Integrated assessment models; Development; Equity.

1. Introduction

The interaction of climate and development threatens to create a paradox: economic development could accelerate climate change, which in turn could block further development, locking the world into existing patterns of inequality as the natural environment deteriorates. The solution to this paradox is far from obvious. What analytical tools are needed to chart a path that leads toward sustainable, low-carbon economic development?

Policies designed to achieve climate stabilization and economic development necessarily involve projections of future physical and economic trends. To a remarkable degree, discussion of climate policy has become a model-driven discourse. A number of increasingly elaborate general circulation models provide detailed forecasts of future climate outcomes, based on broadly accepted scientific principles and a wealth of observational data.

At first glance, it appears that economists have reached a similar level of accomplishment: the integrated assessment models (IAMs) of climate economics give the discussion an aura of quantitative rigour and precision. The broad agreement on underlying principles, however, is lacking in economics. And some of the most important economic relationships cannot be derived from or tested against the available data. On closer inspection, many IAMs are crucially dependent on controversial, often untestable assumptions; those assumptions frequently tilt the models toward endorsing a very slow start in emission reduction. While concerned with overall costs, IAMs generally have nothing to say about regional inequality and development.

This article reviews the implications for climate policy of the climate economics and development literature, focusing on three key areas of judgments and assumptions that are built into a number of leading IAMs. We begin in Section 2 with the treatment of climate science, risk, and uncertainty in IAMs. Section 3 examines questions of abatement technologies and costs, including a focus on the cost effectiveness method of economic analysis. The fourth section discusses ethical issues surrounding the distribution of the costs of emission reductions and adaptation measures. A brief final section offers conclusions and recommendations.

Table 1. Climate economics models reviewed in this study

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

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

2. Science, risk, and uncertainty in climate-economic models

The climate science 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, far-reaching and potentially irreversible. This scientific analysis should be, and typically is in practice, a major input into climate policy choices. Yet it is not the only input that affects those choices.

Very often, the decisions of policymakers take into account both direct scientific predictions and the indirect predictions of climate-economics models, which provide economic interpretations of climate science. We have reviewed 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 maximization, general equilibrium, partial equilibrium, simulation, and cost minimization (see Table 1).

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. *Welfare optimization models* maximize social welfare across all time periods by choosing how much emissions to abate in each time period, where abatement costs reduce economic production. *General equilibrium models* represent the economy as a set of linked economic sectors (labour, capital, energy, etc.); these models are solved by finding a set of prices that simultaneously satisfy demand and supply in every sector. *Partial equilibrium models* 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. *Simulation models* are based on off-line predictions about future emissions and climate conditions; 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. *Cost minimization models* are designed to identify the most cost-effective solution to a climate-economics model.

As a body of literature, these climate economics models suffer from some important limitations that impede their ability to offer accurate and impartial information to the climate policy debate. The first important set of limitations regards a disconnect between the conclusions of climate science and the conclusions of climate economics. Many scientists view climate change as an imminent threat requiring immediate, large-scale action, while many economists favour starting slowly and engaging in careful cost calculations in order to avoid doing too much about the problem. The second set of limitations involve assumptions made by climate-economics modelers regarding the shape and scale of future damages, the interactions between climate mitigation and damages, and employment and trade, and the importance of future generations' well-being.

2.1. The scientific literature and uncertainty

IAMs frequently rely on a damage function, estimating the monetary value of global damages at varying temperature levels. These are typically calibrated to low estimates of damages at moderate temperature increases; for instance, DICE assumes that less than 2% of world output is lost to climate damages at a temperature increase of 2.5°C above 1900 levels (Nordhaus 2008). In contrast to the findings of many IAMs, it is increasingly accepted by climate scientists 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, Chapter 19) projected that:

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[1] See Stanton, Ackerman and Kartha (2009) for a detailed account of our literature review.

- agricultural productivity in low latitudes, especially in Africa, will drop sharply with 2° of warming or less (measuring temperatures in degrees Celsius above 1980–1999);
- agricultural productivity and economic output will drop everywhere above 3°;
- extinction of species will become significant by 2° of warming, especially for coral reefs and arctic animals, and will become widespread by 4°;
- the threshold for eventual loss of the entire Greenland ice sheet, ultimately causing 7 m of sea-level rise, is a sustained temperature increase of roughly 2–4.5°;
- 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), identified two key global turning points. At 2–3°C rates of extinction rise, crop yields decline in developing counties, some tropical forests become unsustainable, and irreversible melting of the Greenland ice sheet is triggered. At 4–5°C risks increase significantly, including a decline in global food production (Stern, 2006). 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 (CO_2-e). Anything lower, he suggests, is impossibly expensive. The higher limit implies a 24% chance of exceeding a temperature increase of 4°C and a 7% chance of more than 5°; the lower limit still allows a 3% chance of hitting 4° and a 1% chance of 5°. Lower temperature thresholds are much more likely to be breached: at 450 ppm there is a 78% chance of hitting 2° and a 18% chance of 3°; at 550 ppm there is a 99% chance of at least 2° and a 69% chance of 3° (Stern, 2006, Box 8.1, p. 195).[2]

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 1 m 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 paleoclimatic 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 °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 would lead to an ice-free Earth and many metres 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 (Hansen *et al.*, 2008).

The climate science literature is grounded in the understanding that real and important uncertainties about climate outcomes cannot be well-represented by an average or most likely result: The 1% chance of reaching 5°C temperature change at 450–550 ppm CO_2-e has a clear and direct relevance to policymaking. Climate-economics models inevitably rely on forecasts of future climate outcomes and the resulting economic damages, under conditions that are outside the range of human experience. Inescapable scientific uncertainties surrounding climate science, like the scale of the climate sensitivity parameter, are commonly represented in IAMs by an average or best-guess value. Climate science cannot rule out low-probability, enormous-cost climate outcome, but climate economics tends to focus on the milder, most likely outcomes.[3]

Even those IAMs that employ probability distributions to represent uncertain parameters may underestimate the worst-case risks. Climate research can only offer a limited number of empirical observations relevant to the estimation of key parameters. As a result, the probability distributions used in some IAMs often under-represent what Martin Weitzman (2007) has called the fat tails of the distribution – meaning that extreme outcomes are much more likely than a normal distribution would imply. According to Weitzman, IPCC (2007) data imply that an atmospheric concentration of 550 ppm of CO_2-e would lead to a 98th percentile chance of 6°C increase in temperature (Weitzman, 2007, p.716).[4]

2.2. Questionable assumptions in climate economics

Climate 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

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[2] These results are confirmed in more recent work: Stern (2008); Hepburn and Stern (2008).

[3] See Stanton, Ackerman and Kartha (2009).

[4] In more recent work, Weitzman has suggested that climate science implies even greater risks at the 95th–99th percentile (Weitzman, 2009). 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.

one country, and for financial investments in abatement and adaptation – essentially, the when, where, and by how much of emissions abatement.

Welfare optimization models offer the most direct answers to 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 emissions profiles and climate outcomes. Regardless of model type, however, there are several complex steps between a projection of future emissions and a recommendation of the best course of action. In order to provide counsel to policymakers, many assumptions are necessary regarding the meaning of human well-being and the scale of the threat that climate change poses to well-being.

2.2.1. Projecting future damages

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.

In many IAMs, damages are assumed to rise in proportion to a power of the change in temperature – typically damages are assumed to be a quadratic function of temperature. Our review of the climate economics literature has revealed no empirical or theoretical basis justifying the widely used quadratic damage function.[5] The Stern Review reports the results of the PAGE2002 (Hope, 2006) model, which uses an uncertain (Monte Carlo) parameter to represent the damage exponent, with minimum, most likely, and maximum values of 1.0, 1.3, and 3.0, respectively. Sensitivity analyses on PAGE2002 show that assuming damages are a cubic function of temperature – that is, fixing the exponent at 3 – increases annual damages by a remarkable 23% of world output (Dietz *et al.*, 2007). The (equally arbitrary) assumption that damages are actually a cubic function of temperature, rather than quadratic, would have a large effect on IAM results and their policy implications.

Investment in abatement and adaptation to prevent climate damages 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.

An important but often overlooked impact of climate policy is the ancillary effect on other outcomes. Reduction of fossil fuel combustion reduces not only carbon dioxide, but also many other air pollutants, improving local air quality and health; inclusion of such ancillary benefits would lower the net cost of climate initiatives, making a more ambitious program of mitigation appear cost-effective (Aunan *et al.*, 2007; Pearce, 2000).

2.2.2. Modelling trade and development

Economic modelling is applied to international trade and development, as well as climate policy. Computable general equilibrium (CGE) models are common in trade policy analysis, and play a role in climate economics modelling as well. CGE models 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 modellers do not use much of the theory beyond the idea that all markets clear at once (that is, that demand equals supply in all markets).[6]

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 modelling 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 (that is, supply equals demand), CGE models apply an artificial, unrealistic procedure for modelling international trade, and eliminate unemployment and no-regrets emission reductions by arbitrary fiat.

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 US demand for paper) between domestic production and imports, and then to distribute the demand for imports among countries that

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[5] See Stanton, Ackerman and Kartha (2009).

[6] On the limitations of the theory, especially for dynamic analysis, see Ackerman (2002).

export that good. While considerable research effort has gone into estimation of Armington elasticities, there are substantial uncertainties and hence wide confidence intervals surrounding the estimates (Hertel *et al.*, 2004).

For policymakers, one of the most important results of economic modelling is the forecast of employment impacts. Much of the political passion surrounding trade policy, or climate policy, reflects the hopes and fears about its effects on employment. Will lowered trade barriers, or new energy conservation and efficiency investments create jobs? Or will a flood of low-cost imports, or the high costs of clean energy investments, eliminate jobs? Most CGE models are silent by design on these fundamental, controversial questions.[7]

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.

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. The standard CGE approach assumes that there are not and cannot be any no-regrets options; this raises the overall cost of mitigation compared to an analysis that acknowledges and measures zero and negative cost abatement technologies. Just as a few trade modelers have begun to experiment with variable-employment CGE models[8], it should in theory be possible to construct CGE models that allow for no-regrets options for emission reduction.

2.2.3. Intergenerational equity

Most climate economic models pay little or no explicit attention 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. The discount rate, in an analysis that derives originally from Ramsey (1928), is composed of two components: the rate of pure time preference, measuring the differential importance we place on future versus present generations, independent of economic growth; and a wealth-based component, depending on the rate of growth of real consumption, reflecting the diminishing marginal utility of income over time as society becomes richer.

Discount rates have a strong impact on climate model results. Analysts who assume a low discount rate, especially

a zero or near-zero rate of pure time preference, have frequently found that active climate protection measures are well worth the price (among others, Ackerman and Finlayson, 2006; Cline, 1992; Stern, 2006). On the other hand, those who assume a high discount rate, especially a significantly positive rate of pure time preference, have frequently found that only modest climate protection measures are cost-effective in the near future (among others, Nordhaus, 2007c; Tol, 2008). The literature on discounting and intergenerational equity is extensive; for reviews, see Portney and Weyant (1999); Stern (2006, Chapter 2 and appendix); Ackerman *et al.*, (2009); and Stanton *et al.*, (2009).

Choices about the discount rate reflect value judgments made by modellers. Most obviously, the rate of pure time preference is a judgment about the value of present versus future generations. Indirectly, the other component of the discount rate has parallel implications: a larger wealth-based component reflects a greater emphasis on equity, assuming that an increase in income to a poorer person is more valuable than the same absolute increase in income to a richer person. But when combined with the common assumption that the world will grow richer over time, discounting then 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 many IAMs, even those that explicitly treat the regional distribution of impacts; see Section 3 of this article.)

3. Analysing abatement options

Using scientific projections and economic interpretations of scientific outcomes, policymakers have the information necessary to establish limits for global greenhouse gas emissions in future years. A global emissions budget, however, sheds no light on questions of which abatement technologies to prioritize and 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 climate effects.

Likewise the abatement of one unit of greenhouse gas emissions will have the same effect regardless of technological or geographic origin. Analysis of abatement often requires technical information on a plethora of abatement technologies, and on each region's potential for low-cost abatement and its track record in implementing abatement measures. (Both adaptation costs and the ancillary benefits of abatement, discussed above, are likely to be site-specific, requiring additional information on local opportunities and impacts.) Note that the question of who will pay for abatement is quite separate from where it occurs. To find the most cost-effective abatement solution to

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[7] See Stiglitz and Charlton (2004) for a critique of the use of CGE models in modeling international trade.

[8] For trade models that attempt to move beyond the fixed employment assumption, see Fernández de Córdoba and Vanzetti (2005) and Polaski (2006).

the global climate problem, the ability of each country to pay for emissions reduction measures must be treated as distinct from local abatement costs.

3.1. 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, ppm CO_2-e 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. A cost effective strategy is the most efficient (or cheapest) means to reach a stated goal and is usually implemented through regulation.

Cost-effectiveness analysis 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.

Cost minimization models are the IAMs best suited to cost-effectiveness analysis, while welfare optimization models are most closely associated with cost–benefit analysis. The latter answer the question of how much global emissions abatement to engage in by searching for a level of emissions that 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.

Cost-effectiveness analysis usually relies on a measure of the marginal cost of carbon reduction.[9] 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.

There are several well-known technical projections of the cost of abatement over time and across sectors or abatement measures; in some cases differentiated cost projections are available for different regions or countries.[10] 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. Many IAMs use this abatement cost literature to calibrate the pace of technological change and cost of abatement measures.

The best known of these abatement cost projections, the McKinsey cost curves (Nauclér and Enkvist, 2009), plot potential for abatement by cost of abatement measure, in order of marginal cost. According to their projections, the abatement measures sufficient to achieve a 450 ppm CO_2-e stabilization trajectory – given business-as-usual growth in emissions – would have a marginal cost of €60 per ton of CO_2-e in 2030.[11] This is to say that all of the measures necessary to achieve this level of abatement have per unit costs no higher than €60 per ton of CO_2-e. Nearly one-third of the emissions reductions with price-tags of €60 or less have zero or negative costs, primarily energy efficiency improvements. The *average* cost of their package of potential abatement measures is only €4 per ton of CO_2-e, far below the marginal cost of the most expensive measure they considered.

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

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[9] 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 based on the next abatement measure available, having exhausted all less expensive measures, and the average cost is considerably lower than the marginal cost.

[10] See especially a series of reports on marginal abatement curves by McKinsey *et al.*, (http://www.mckinsey.com); IPCC (2007) Working Group III; and the International Energy Agency's projections in the 2008 World Energy Outlook (http://www.iea.org/).

[11] The abatements identified in the McKinsey analysis would reduce emissions by 38 Gt CO_2-e in 2030. The 2009 McKinsey cost estimates assume that oil costs $60 per barrel; a higher oil price makes energy savings more valuable, and hence reduces the net cost of abatement.

political will regarding both domestic emissions reductions and investments in abatement measures abroad. Twenty-two percent of all low-cost abatement potential for 2030 comes from China; another 46% comes from the rest of the developing world, mostly in reductions to emissions from forestry and agriculture. Developing countries have more potential for abatement 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. Funding from richer countries will be essential to realize the potential for abatement in developing countries (Enkvist *et al.*, 2007).

3.2. Vertical damages and the social cost of carbon

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; UK Department for Environment Food and Rural Affairs, 2007).[12] 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 society can be protected from spending too much on preventing climate catastrophe.

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 1). 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. Cost-effectiveness analysis is a closely related approach that avoids the shadow price method's reliance on price incentives to do the heavy lifting.

3.3. The new low-carbon development path

There is a rich strain in recent development literature regarding anecdotal accounts of the potential for mitigation
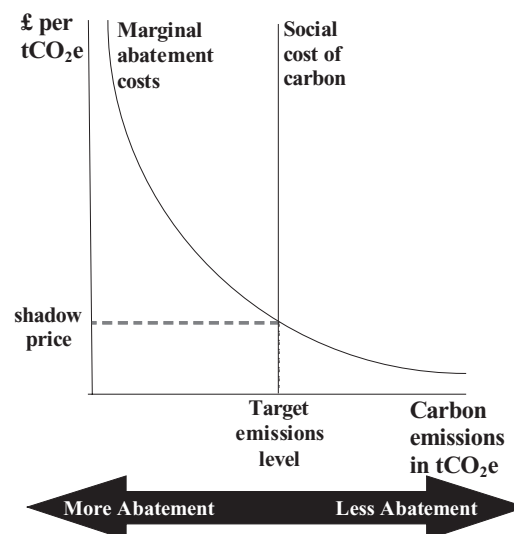

Figure 1. Vertical social cost curve.

and adaptation measures. Kok *et al.* (2008) summarize this literature and advocate for development policies that reduce vulnerability to climate damages and promote low-carbon technologies, but warn that examples of such policies are few and far between.[13] Policies on a national or regional scale are particularly uncommon; Brazil's alcohol fuel programme 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 Clean Development Mechanism is by far the largest of the existing financial flows for climate protection in developing countries, but at $8 billion per year as of 2007, it is too small by more than an order of magnitude to finance the needed, cost-effective abatement opportunities; see Ackerman (2009). The need to mainstream climate change into international agreements and 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.

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[12] For a critique, see Stanton and Ackerman (2008).

[13] See also Metz and Kok (2008).

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. Many policies straddle the boundary between climate and development goals; there has even been debate about whether industrialized countries' support of adaptation should be viewed as development aid or as climate policy (Levina, 2007).

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 the development issues, historical responsibility, and commitment to 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. A low-carbon development path will most likely combine less expensive abatement measures available in developing countries with financing from higher-income countries.

4. Paying for emissions reductions and adaptation measures

The questions of how much emissions to abate and where to abate them are a matter for science and technology but the question of who should 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, then 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: which 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?

4.1. The role of equity in economic analysis

Climate-economics models quantify the expected climate damages and abatement costs under various mitigation scenarios. Many IAMs offer policy advice in the form of an optimal scenario: a recommended course of action, including a schedule for abatement, which is said to achieve the maximum possible human well-being across the centuries. Such a scenario could be interpreted as a statement about equity over time, between present and future generations. What advice do these models offer on equity over space, i.e. the distribution of burdens between rich and poor regions of the world today?

The answer is determined in part by a little-known technical procedure, Negishi weighting, which is crucial to the workings of many climate-economics models.[14] In effect, Negishi weights freeze the current distribution of income between world regions. Without such a constraint, IAMs that maximize global welfare would recommend equalization of incomes around the world. With Negishi weights in place, these models instead recommend the course of action that would be optimal if global income redistribution cannot and will not take place. This recommendation has policy relevance only if decision makers agree that income redistribution is impossible or impractical.

Similarly, the damage functions of IAMs are not without ethical content. For example, estimates of damages used in DICE-2007 (Nordhaus, 2007b) include the health effects of climate change, introduced into the model as years of life 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

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[14] For a detailed discussion of Negishi weighting in IAMs see Stanton (2009).

Table 2. Discounted value of deaths in DICE-2007

A Death in Sub-Saharan Africa			
Age at death	1	25	50
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
2005	$2,051,173	$1,919,120	$1,525,928
2055	$231,090	$210,466	$159,213
2255	$591	$502	$340

(The leftmost column of the data rows, labelled vertically "Year of death", applies to both sub-tables.)

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

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.

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% of the per capita income in the host region." (p.135) The ethical implications of these types of assumptions – 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% of GDP to avert 2.5°C): "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 on 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 – a region's inability to pay to avert damage, or indeed to adapt and thereby prevent damage, or to repair damage after it has occurred, does not mean that their 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).

4.2. 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 the sum of its actual individual emissions, for all residents with emissions less than the cap, and the target for individual emissions, for all residents with emissions 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 the goal of equal rights to emit with the recognition that it takes time to change past practices. Each country is initially allocated emission rights based on its past per capita emissions. Over time, the allowable total of global emissions contracts while all countries converge to the same level of 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:

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 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 by a team of researchers at Tsinghua University in Beijing, 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). Although expressed in different terms, this proposal is similar in substance to the earlier Brazilian proposal to allocate Kyoto Protocol reduction targets among developed countries in proportion to their cumulative historical emissions (Rosa *et al.*, 2003).

5. 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 among 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.

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 industrialized world but a few 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 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.

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