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On the Economics of Climate Policy

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Working Paper No. 234

On the Economics of Climate Policy

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of
the Economy and the State**

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On the Economics of Climate Policy¹

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I. Introduction

Energy is essential to the maintenance and spread of economic welfare. At a point in time, individuals in richer countries such as the US and Canada use much more energy than individuals in poorer countries. Over time, long run growth in living standards is strongly associated with rising energy use. There is little to indicate that these patterns might change, so that future growth and the escape of developing countries from current levels of poverty hinge on the existence and use of abundant energy supplies.

Yet rising worldwide demands for energy run up against new evidence of the social costs of energy use. The broad consensus of scientific research is that the continued dependence of economic activity on carbon-based fuels and their associated emission of greenhouse gases (GHG) create risks of substantial future changes in earth's climate, along with associated harm to the welfare of future generations. This "new" knowledge of anthropogenic climate change has motivated national and international efforts to regulate the use of carbon-based energy sources, and to promote the development and use of "clean" energy alternatives. For example, the Obama administration recently "committed" the US to achieve an 80 percent reduction in carbon emissions by 2050, even while enabling legislation to begin the regulation of such emissions languishes in Congress. In Europe, an incipient "cap-and-trade" market for emissions permits is in place, while California is considering unilateral action along the same lines. Broadly-based international efforts have met with little success, as evidenced by the failure of the Kyoto (2000) and Copenhagen (2009) negotiations to achieve implementable frameworks for reducing GHG emissions.

These initiatives must confront several daunting challenges to the successful design and implementation of a useful energy-climate policy. First, current generations—who are the ones that get to decide—must be convinced to forego use of abundant carbon-based energy sources in order to mitigate uncertain harm to generations of the distant future. No such sacrifice has ever been made. Second, even if current generations are convinced that mutual sacrifice would be a good thing, effective policies require the largely voluntary yet global cooperation of nations in an environment where non-cooperation offers substantial rewards. Again, we are unaware of the success, or even the formation, of similar policies.

These problems are created by the fact that climate is a “global public good.” In terms of climate impact earth’s atmosphere doesn’t much care where GHG emissions come from—a ton of carbon emitted in India has the same impact as one from Canada, so the atmosphere is over-used by all in a classic example of the tragedy of the commons. Meaningful efforts to successfully correct this externality must then hinge on collective and harmonized action by nations world-wide. Yet efforts at cooperation are hampered by the same free-rider incentives that created the problem in the first place—the benefits of carbon-based energy use are current and highly focused, while the social costs are greatly delayed, difficult to discern or measure, and highly dispersed. In addition, as we argue below, the social costs of climate change and the benefits of mitigation policies are not uniform, which leads to divergent valuations of social investments in “climate capital.” This is especially true when, as here, the distributions of returns on such social investments are country-specific and highly uncertain. Then policies such as widely-discussed carbon taxes or cap-and-trade schemes offer much different risk-reward tradeoffs to developing countries, such as China or India, than to developed countries like the US. These divergent valuations help explain the current lack of progress in international

negotiations over climate policy, such as Copenhagen (2009), and what we believe are the limited prospects for cooperation going forward.

From (very) high altitude, the economics of anthropogenic climate change is a standard problem of externality—current users of carbon-based fuels do not bear the environmental costs of energy consumption, so they use too much of the stuff, and too little of “clean” alternatives. The problem occurs because some resource—here the atmosphere—is unpriced and so overused. The idealized textbook market intervention is to price the overused resource, equating the private and social costs of its use. This can be accomplished via a Pigouvian tax (or its equivalent) equal to the marginal external cost of using a unit of carbon-based fuels. The resulting ideal “carbon-price” would exactly balance the benefits of additional carbon emissions, which occur now, against their costs, which are spread over the near and distant future.

This basic solution to the externality problem is familiar and straightforward. It is central to virtually all serious national and international policy proposals to deal with climate change, including the Waxman-Markey⁵ and Lieberman-Warner⁶ bills in the US House and Senate, the design of cap-and-trade policies in the EU, and the tentative framework discussed in the Copenhagen negotiations. But its conceptual simplicity is superficial—the actual design and implementation of such policies faces daunting challenges and unresolved questions. Our analysis seeks to contribute to a number of unresolved issues in the design and effects of policies to mitigate climate change. These include:

1. Valuing future costs: The social costs of current GHG emissions are uncertain and spread over the distant future. How should current generations value the costs of climate

⁵ <http://www.govtrack.us/congress/bill.xpd?bill=h111-2454>

⁶ <http://www.govtrack.us/congress/bill.xpd?bill=s110-2191>

damage, which will fall mainly on future generations? Should the future benefits of investments in “climate capital” be discounted at market rates or, as some have argued, at much lower rates? How will these valuations differ across countries, virtually all of which must cooperate to achieve efficient policy outcomes?

2. Uncertainty: How does the great uncertainty regarding the extent and costs of future environmental harm affect current strategies, social investments, and valuations?
3. Catastrophic climate change: Among the uncertainties is the possibility of catastrophic outcomes that could greatly reduce future living standards or impair the ability of certain regions to support life. How should current policy value and mitigate these possibilities? How do policies meant to deal with catastrophic outcomes interact with other policies?
4. Market responses to climate policies: At its barest level, “carbon pricing” is a market-based solution that relies on market responses to efficiently designed incentives. How will markets respond to policy-generated incentives? Will market responses enhance or constrain the effects of policies?
5. Innovation incentives, policy design and the costs of delay: How does an efficient policy affect research incentives and the pace technical progress in alternative energy sources and in mitigation? If technical breakthroughs are likely to be the ultimate solution to the energy “problem”, are incentives to innovate harmed by delays in implementing an optimal policy? How should the prospect of future innovation affect current policy?
6. The role of government: Given the importance of energy use to economic welfare and growth, even market-based solutions imply a large expansion of the role of government in economic activity, and a transfer of resources from private to public hands. How will

this transfer affect overall efficiency? Given the public-good nature of basic research, and especially for basic research affecting energy and climate, the decisions of government entities will impact the level, pace and direction of technical progress in energy use and mitigation. How will those decisions be made?

II. Basic Features of Efficient Climate Change Policies

The scientific foundations for anthropogenic climate change indicate that current emissions of GHGs create environmental and other costs that are (1) greatly delayed, (2) very long-lasting, and (3) highly uncertain.⁷ This is because the flow of CO₂ to the atmosphere has a long lasting impact on the stock of atmospheric CO₂, as reabsorption is very slow. In turn, the growth in global temperature lags the atmospheric stock of CO₂ because, for example, melting of ice caps reduces earth's albedo (reflectivity) and oceans warm slowly. Many costs are likely to lag a rise in temperature—for example, rising sea levels would be driven by melting of ice caps, which would follow a prolonged warming period. Finally, uncertainty as to environmental feedbacks and other impacts includes the prospects for catastrophe in various forms. Because of these features, policies that would mitigate these effects must balance costs and benefits over hundreds of years, and subject to large and costly contingencies, which make the problem of policy design a good deal more daunting than the usual project evaluation.

To illustrate central elements of dynamic carbon pricing and its connection to key assumptions about preferences, growth and technology, consider a simple certainty framework in

⁷ See Archer (2007) and (2009) for useful summaries of the state of climate science research on global warming.

which the target cap on atmospheric concentration of GHGs at some endogenous future date T (say in $T=200$ years) is the goal of environmental policy. Denoting the concentration of GHGs at date t by Q_t , this terminal condition is $Q_T = \bar{Q}$. Stated in this way, the optimal policy solves a Hotelling problem for allocating the use of an exhaustible resource over time—where here the exhaustible resource is the capacity of the atmosphere to “safely” hold a given concentration of GHGs.⁸

Let the private social (consumer plus producer) surplus from current emissions, q , be $V_t(q_t, c_t, y_t)$ where c_t is the unit cost of carbon-free energy sources at date t and y_t is income. Finally, let the technology for mitigating emissions be represented by the cost $C_t(s_t \mu_t^{-1})$, where s_t is the amount of period- t emissions avoided through mitigation activities and μ_t indexes the evolving efficiency of mitigation—higher values of μ_t reduce the costs of emissions mitigation. For example, s_t might be the amount of period t emissions that are eliminated by sequestration or other technologies, and μ makes the process more efficient. With these definitions, the policy problem is to maximize the present discounted value of social surplus.

$$(1) \quad \begin{aligned} \underset{q, s}{\text{Max}} W &= \int_{t=0}^T (V_t(q_t, c_t, y_t) - C_t(s_t \mu_t^{-1})) e^{-rt} dt \\ \text{s.t. } \dot{Q}_t &= q_t - s_t - aQ_t \text{ and } Q_T = \bar{Q} \end{aligned}$$

where r is the rate of interest used to discount future environmental costs (the rate of return on investments in environmental capital) and a is the rate at which atmospheric GHGs are

⁸ There need not be a fixed target level of GHG for this analysis to apply. As long as the effects of climate change are simply a function of the stock of GHG at some future date (200 years in our example), the optimal program will need to solve this same Hotelling problem given the optimal level of GHG at the terminal date.

reabsorbed. We shall have much more to say about r later, but for now we simply take it as given without pondering how large or small it could or should be.

The basic solution to (1) has a familiar structure:

$$(2a) \quad \begin{aligned} V'_t(q_t, c_t, y_t) &= P_0 e^{(r+a)t} \\ \mu_t^{-1} C'_t(s_t \mu_t^{-1}) &= P_0 e^{(r+a)t} \end{aligned}$$

In (2a) both the marginal value of using and the marginal cost of eliminating a unit of emissions are equated to the period- t “carbon price” $P_0 e^{(r+a)t} = P_t$, which represents the scarcity value of a “unit” of the otherwise unpriced atmosphere. This price is the outcome of an ideal Pigouvian tax or cap-and-trade system, so that P_t equates the marginal benefit of q to current users and the (present value of) incremental costs imposed on future generations.⁹

Carbon Pricing, Timing and the Returns to Innovation

The fact that the carbon price rises at the rate of interest (plus absorption) is a well-known property of this and other exhaustible resource problems.¹⁰ It is a condition for intertemporal efficiency in the use and mitigation of emissions, equating the value of benefits from creating incremental emissions (due to energy use) to the present value of costs. Less appreciated is how this property of an optimal policy impacts the social value of innovations, incentives to innovate and the cost of waiting to implement the policy.

To fix ideas with a not-entirely-fanciful example, think of a current investment in technology that could eliminate one unit of carbon emissions at some arbitrary future date, t —a one-period

⁹ Nordhaus (2007) and (2008) are good summaries of the state of economic modeling applied to global warming and climate policy. Many of the same analytical tools appear in Stern (2006).

¹⁰ The original statement is in Hotelling (1931).

“carbon eating tree.”¹¹ The present value of this unit reduction in future emissions is

$P_t e^{-rt} = P_0 e^{(r+a)t} e^{-rt} = P_0 e^{at}$, which is independent of the interest rate, r . If $a=0$, the present discounted value of the innovation is also independent of how far in the future it pays off, t , because the value of the gain rises at the interest rate. And if $a>0$ the present value actually rises with t because the time- t value of the innovation rises faster than the interest rate. In effect, the value of the innovation is undiscounted.

The result is even stronger if innovation is scalable. Think of an innovation that would reduce the incremental cost of mitigation at some future t , raising μ_t by $d \ln \mu_t > 0$. The present value of this cost reduction (per unit change in $\ln \mu$) is

$$\begin{aligned} & e^{-rt} \mu^{-1} C'_t(s_t \mu_t^{-1}) s_t \\ &= e^{-rt} P_t s_t \\ &= P_0 e^{at} s_t \end{aligned}$$

Here the unit value of the innovation is independent of r , and also of t if $a=0$, but the reduction in incremental cost is scalable because it applies to all units, s_t . But s_t rises over time because P_t is increasing, so the present value of the innovation also rises with t —the gain has larger present value the farther in the future it occurs. Applied to all periods, a scalable technical advance in mitigation that applies from the present day forward is worth

$$(3) \quad W_{\ln \mu} = P_0 \int_{t=0} s_t e^{at} dt$$

Even with $a=0$, the value of the gain applies to the quantity of mitigation in all future periods with equal weights. If $a>0$ then future periods get more weight than the present. And of course

¹¹ E.g. Dyson (2008).

the result applies to other types of innovation, such as an advance that would improve the consumption efficiency (surplus) per unit of emissions, like a change in fuel efficiency of cars. All such gains are valued at the rising Pigouvian price P_t , which “undoes” the effect of discounting in present value calculations.

These conclusions may appear anomalous, and it is easy to extend the policy problem (1) to include factors that would cause P_t to rise more slowly. For example, if we amend the optimal policy to include possible environmental damages $D(Q_t)$ from rising atmospheric concentrations along the trajectory to T , then the current optimal carbon price is continuously updated, incorporating the impact of current emissions on future damages:

$$\frac{d \ln P_t}{dt} = r + a - P_t^{-1} D'(Q_t)$$

where $D'(Q_t)$ is the current period marginal damage from emissions, equivalent to the effective current period “rental price” of atmosphere. This reduces the growth rate of P_t relative to the standard Hotelling solution, but without negating the broader point, which is that innovations yield greatest value when the carbon price is high, and in the optimal policy that price is rising.

The central lesson about valuing progress in (3) is simple, but it has important implications for interpreting both the form of policy responses to climate change as well as the urgency with which those policies are implemented and the costs of delay. The slow progress of international negotiations in gatherings such as Kyoto and Copenhagen is widely lamented, as is similarly slow progress in crafting and adopting enabling legislation in the US and other

countries. Do these delays adversely impact incentives to find “solutions” in the form of technologies that would reduce the carbon impact of energy consumption? Is a sense of urgency warranted?

If we assume that slow progress toward implementing a policy is just that—slow progress that will eventually result in widely applied carbon pricing—then the costs of delay are small. To illustrate, use (3) for the present discounted value of a cost-saving innovation that requires substantial up-front R&D effort. Realization of these incentives requires two things: an initial incentive, P_0 , that signals the current scarcity value of emissions, and a commitment to a time path for that value in the future. Given these, delaying the start of this payoff for d years would not much affect its present value, even if the initial d years of a payoff stream were foregone. And if the whole program is simply pushed back the payoff would likely rise because the initial price P_d would increase by more than simple interest (because interim unpriced emissions tighten the ultimate constraint), which also raises s . The result is that the current value of innovation incentives and the social gain from innovations are not much harmed and may even be increased by delay.

This analysis assumes that an optimal carbon pricing program is eventually implemented—that negotiations and legislation result in something useful in terms of price signals and commitment to policy. The message is not that delay is costless—the tighter constraint and necessarily higher carbon price caused by delay demonstrate the costs—but rather that the returns to climate-related innovations are not much reduced by delay in implementing well-designed incentives. And if the ultimate efficiency gain is likely to derive from currently unforeseen innovations driven by carbon pricing, rather than simply by business as usual along a

rising price path, it is likely that delays of a few years don't much impact that outcome. Put differently, it is far more important to get the form of policy right—including believable commitments to the level and time path of future carbon prices—than to get a policy done quickly.

Factors Affecting the Impact of Policy

Conditions (2a) for the rate of change price of the carbon price embed the properties of evolving demand and supply for carbon-based fuels, as well as changes in the availability of substitutes, z , and the evolution of technology. It's worth being explicit about these, because expectations of how demand and technology will evolve in the future are essential ingredients of current policy and the level and timing of mitigation activities. Using the usual notation for time rates of change, we have

$$(2b) \quad \begin{aligned} \dot{q}_t &= -E_t[r + a] + \sigma_t \dot{c}_t + \eta_t \dot{y}_t \\ \dot{s}_t &= \phi_t[r + a] + [1 + \phi_t] \dot{\mu}_t \end{aligned}$$

Here, σ is elasticity of emissions with respect to the cost of its substitute, c , η is the income elasticity of demand for emissions generating activities, ϕ_t is the elasticity of mitigation supply (the inverse of the elasticity of marginal cost) and E is the elasticity of emissions with respect to its price, which embeds both supply and demand responses to P .¹²

Equations (2b) have several important implications. First, absent technical progress in reducing emissions ($\dot{\mu}_t = 0$) and with negligible reabsorption ($a=0$), the growth rate of

¹² In a competitive market E will be given by the harmonic sum of the supply and demand elasticities.

mitigation is proportional to the rate of interest. But with $\dot{\mu}_t > 0$ the growth rate of mitigation is augmented by anticipated technical progress (the rate of decline in costs) in emissions reduction. Given the dependence of emissions mitigation on technology and research, and expectations that costs of emissions reductions actually will fall over time, this means that “waiting” to achieve emissions reductions is a central element of policy. In a broader context, however, the magnitude of μ is endogenous to current policy, because it is an outcome of current and future R&D efforts, and our previous discussion indicates that incentives to innovate are powerful, provided that innovators can collect on the value of their innovations.

Similarly, the benefits of deferral are larger when ϕ_t (the elasticity of mitigation supply) is large, and especially when large values of ϕ_t are likely to evolve from future technical advances. Large values of ϕ_t mean that marginal costs of mitigation rise slowly—mitigation activities are easily “scalable”—so there is not much cost to sharply ramping up mitigation in later periods when reduced emissions are most valuable. But when ϕ_t is small the marginal cost of mitigation increases rapidly with s —there is a large cost penalty if mitigation efforts are concentrated in fewer periods. Then it is worthwhile to do things in smaller pieces by spreading mitigation activities over time. This means ramping up sooner rather than later.

This effect of ϕ_t is the “certainty” equivalent of a broader point about scalable technologies—they can be deployed as needed on large scale without much cost penalty. As we show below, development of highly scalable (high ϕ) technologies is especially valuable if we extend this framework to incorporate uncertainty and the possibility that future environmental effects of GHGs may turn out to be much more costly than currently anticipated, or that low-

probability but high-damage outcomes may occur. Then scalable technologies to reduce emissions have high option value, precisely because they can be deployed on a large scale when mitigation is most critical. Notice also that technical advances that raise ϕ and $\dot{\mu}_t$ are complementary—the social benefits from higher $\dot{\mu}_t$ are proportional to ϕ , and conversely.

Similar implications apply to the “value” side of (2b). Since the price of carbon rises at the “net” interest rate $r+a$, this price rise induces conservation in proportion to the price elasticity E . Note that E embeds both production and consumption responses to carbon pricing—for example, the fact that carbon-based fuels are abundant and in fairly inelastic supply on the world market indicates that E is likely to be quite small. Together with demand growth ($\dot{y}_t > 0$) on the world market, the implication is that substantial conservation relative to business-as-usual is unlikely. Then policy success is critically dependent on technical advances that would promote mitigation (ϕ and μ) or substitution ($\sigma_t \dot{c}_t < 0$). In other words, the point of pricing is not so much to induce conservation on the demand side—which is likely to have small effects—as it is to guide the research incentives that will result in clean energy alternatives.

Evolving Expectations and Changing Incentives

For a given rate of interest the rate of growth of the optimal carbon price is determined. The other key to incentives is P_0 —the current carbon price—which determines the level of the entire price path. This is affected by the entire array of technology and substitution effects, and the way they evolve, as in (2b). By the usual Hotelling analysis, things that reduce the growth of q or raise the growth of s reduce P_0 and delay the ultimate date T when net additions to Q

cease. For example, the expected emergence of technologies (ϕ) that make s more scalable allow for lower net emissions along a flatter path, making T longer, and so on. Equivalently, these effects reduce \bar{Q} and T for a given initial incentive, P_0 .

Though we have little to add to the debate over the relative merits of carbon taxes versus cap-and-trade schemes—see Nordhaus (2007) for a good discussion—our framework does highlight some of the key issues. While we have framed the optimal policy in a certainty-equivalent framework, the fact that the optimal P_0 depends on expectations of future market responses means that an efficient policy will adjust the current price level as information evolves, just as a new “find” that will increase the future availability of an exhaustible resource (such as oil) will reduce its current price. In an ideal cap and trade framework in which total acceptable emissions \bar{Q} are fixed and unchanging, the collection of information and the formation of these expectations is decentralized to market participants—a clear advantage in terms of incentives. But the possibility of governments manipulating the variable they control, \bar{Q} , invites rent-seeking, which is the foundation of most economists’ critique of cap-and-trade schemes. In contrast, with tax-based carbon pricing the formation of such “expectations” and hence the evolution of prices is left to government. There is little reason to believe that governments would do well in this regard, and the opportunities and incentives for inefficient choices and rent-seeking appear to us just as powerful with taxes as with cap-and-trade.

Discounting

Foremost among factors affecting the strength of initial incentives, P_0 , is the rate of interest, r , which determines the entire expected price path. Higher r means low P_0 and a gradual ramping up of incentives and responses, and conversely. Ignoring a , for any given future

marginal damage from incremental emissions, say $P_T = \$500$ per ton of CO₂ emissions in $T=100$ years, the initial carbon price is $P_0 = e^{-rT} P_T$. If we base r on historical market rates of return on physical and human capital, then a value in the neighborhood of $r=.06$ is reasonable. This yields $P_0 = \$1.24$ if $P_{100} = \$500$. Conversely, a carbon price of \$10.00 today would imply a carbon price of roughly \$4,000 in 100 years. If $a > 0$ then the growth in carbon prices would be even greater. In contrast, the UK government's 2006 *Stern Review of the Economics of Climate Change* advocated $r = .015$, based on the *Review's* ethical notion that it would be improper to heavily discount the costs that current actions impose on future generations. Then $P_0 = \$500 \times e^{-.015 \times 100} = \112 , which is almost 100 times larger than with $r=.06$. As pointed out by Nordhaus (2007a) and Weitzman (2007), among others, this choice of a (very) low discount rate for investments in climate capital accounts for virtually all of the differences between the *Stern Review's* draconian recommendations for current action and the more gradualist policies advocated by others. Much then hinges on the choice of r , which we take up below.

III. Valuing Future Climate Damages

The fact that current economic activity and policy affect uncertain climate outcomes and costs over vast time periods is perhaps the most daunting challenge of climate policy. Possible future outcomes—including the possibility of environmental catastrophe that could harm large future populations or greatly reduce productivity—must be both envisioned and valued, and then balanced against the current cost of mitigating such harms.

We address three issues related to the current valuation of uncertain future damage. First, given the possibility of various types of catastrophes, what does economic analysis say about the costs that should be incurred today in order to avoid them? At standard discount rates, events that have even substantial impacts on productivity and population-wide living standards in the distant future have only small present value. We show below that these values substantially increase, however, when climate-related damages are unequally distributed, when future lives are at risk, and when we add uncertainty as to when the damaging events might occur (holding constant the expected time to occurrence). Even at “market” rates of discount, not-implausible values for the magnitudes of future catastrophes imply substantial current willingness to pay to avoid them.

We then turn to the controversial topic of discounting and the valuation of climate investments with uncertain returns, where we find that discount rates for investments in climate capital can be unusually low, reflecting their insurance value. Combined with the possibly high costs of future catastrophes, the present value of particular investments in climate capital can be very large. We also find that distribution matters. The global public good nature of harmonized climate policies is challenged by heterogeneity of valuations—projects that have high insurance value to developed countries because they reduce future risks are likely to be much less valuable to developing countries, for whom the possibility of rapid economic growth is likely more important.

The Costs of Future Catastrophic Outcomes

Future catastrophic outcomes may include substantial damages to productive capacity, sustained reductions in economic growth, threats to living standards or lives of particular populations, or permanent environmental harm that reduces welfare for any given level of economic activity. To frame these possibilities, we begin with the standard infinite-horizon model of intergenerational utility that underlies most work in economic growth and climate policy. Write the current value of generational welfare over the indefinite future as:

$$(4) \quad U_0 = \int_{t=0}^{\infty} u(c_t) e^{-\rho t} dt$$

In (4) ρ is the rate of time preference, or in an intergenerational context the rate at which earlier generations discount the well being of later ones, and c_t represents the per-capita flow of goods and services (consumption) available to generations alive at future date t , which may include valuations of environmental factors. We continue to abstract for the moment from issues of uncertainty.

One form of calamity that can be represented in (4) is a permanent reduction in future living standards that is known to commence at some future date T , say in 100 years. So assume that future productivity is reduced by a constant percentage $d \ln c$ from T onward. For example $d \ln c = -.01$ would represent a permanent 1-percent reduction in per-capita income and consumption. Assume a constant elasticity of the marginal utility of consumption, m , and steady state economic growth of g . Then we can apply the Ramsey Equation linking the equilibrium interest rate to time preference and economic growth, $r = \rho + mg$. The current value of this harm as a fraction of current (time zero) national income is:

$$(5) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{e^{-(r-g)T}}{r-g} d \ln c$$

where $(r-g)^{-1} d \ln c$ is the damage valued at date T and $e^{-(r-g)T}$ discounts the date- T value to the present, allowing for economic growth. How large is (5)? Assume $r=.06$ and $g=.02$ —fairly standard values in a growth framework—and let $d \ln c=.01$ (a one percent permanent reduction in future incomes). Then with $T=100$ years the right side of (5) is equal to .0046, or about half of one percent of current income. For the US with a national income of about \$13 trillion, this implies a present discounted value of future harm of about \$59 billion. Viewed as a long term project to avoid such damage, the expenditure flow at 6 percent interest is about \$3.6 billion. Cutting the horizon to $T=50$ years substantially impacts the estimates. Then a permanent 1 percent reduction in future income is worth about 3.4 percent of current income (\$440 billion), or a flow expenditure of \$26.4 billion per year.

Adding an element of uncertainty about when such climate-related damages might occur substantially raises the present value of avoiding them. To demonstrate this point in a simple way, hold constant the expected time until damage occurs at $T=100$ years, but assume that the damage is equally likely to commence at any future date. This implies an arrival rate (hazard) for the damaging event of $h=T^{-1}$. Then the present value of damages as a fraction of current income is:

$$(6) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{1}{1+(r-g)T} \frac{1}{r-g} d \ln c$$

Using the same values as above and $T=100$, a permanent 1 percent reduction in living standards with expected time to occurrence of 100 years has present value equal to 5 percent of current income, which is roughly 11 times greater than when the damage was known to commence in 100 years. This is worth about \$650 billion to the US in 2010, or a flow expenditure of \$39 billion per year at 6 percent interest. At $T=50$ ($h=.02$) the cost is 8.3 percent of current national income, or a flow of \$65 billion. Clearly, uncertainty over the time at which climate change will have an adverse effect can be very important.

Formulas (5) and (6) express the current value of marginal losses in future per capita consumption—everyone consumes one percent less than otherwise. This is consistent with most of the existing analysis of valuing climate costs, where those costs are framed in terms of reductions in future GDP, or costs as a fraction of GDP, as if the burden of climate impacts is equally spread among the future population. But much of the concern about climate-related damages has to do with the distribution of harm, where some groups are harmed much more than others. Concave $u(c)$ means that reductions in c have rising marginal cost to those who experience them, so that a given reduction in aggregate income is more costly when it is highly concentrated. For example, with $m=2$ a catastrophe that reduces incomes by half among 2 percent of the population is twice as costly as an across-the-board reduction in living standards of one percent, even though both events reduce overall per-capita income by the same amount (one percent). Taken a step further, a climate-related catastrophe that reduces future national incomes by one percent by killing off 1 percent of the population while leaving others unharmed may be very costly. The reason is that such catastrophes are not “marginal,” reducing everyone’s income proportionally. Instead they wipe out consumer surplus—or in the extreme case the value of life—for a swath of the population.

How costly are such population-threatening catastrophes? A framework for thinking about these issues is provided by the economic literature on the value of a statistical life (VSL), which measures people's willingness to pay for a reduction in the probability of death that would save one "statistical life." For example, if in a population of 10,000 individuals each would be willing to pay \$600 per year to reduce the per-year probability of accidental death by 1 in 10,000, then $VSL = \$6$ million. In fact, this is the value used by the US Environmental Protection Agency for cost-benefit analyses of regulations or projects that would reduce mortality risks. Murphy and Topel (2006) use this value to calibrate the value of a life-year $v(c) = u(c) / u'(c)$, which is the "consumer surplus" achieved by being alive and consuming amount c , where c includes leisure and other factors that people value. They find that the value of a life year is about six times current income, so if we think of $v(c) = \psi(c)c$ the data suggest that $\psi(c) \approx 6$ at current income levels. Then the above calculations would increase by at least a factor of 6 for life-threatening events that cause an equally-calibrated reduction in future "income." The analyses in Murphy and Topel (2006) and Hall and Jones (2007) also indicate that $\psi(c)$ rises with income, so that the value of life is income elastic. Then if future generations are richer than us as a result of economic growth, the value of lives saved from mitigating future catastrophes will be proportionally greater than today. For example, an income elasticity of $\eta=1.2$ and long run economic growth of 2 percent per year yields $\psi(c) \approx 9.0$ in 100 years. The result is that a randomly occurring event that causes a "concentrated" change in future costs because of climate-related mortality has much higher current value:

$$(7) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{\psi(c_0)}{1 + (r - \eta g)T} \frac{1}{r - \eta g} d \ln c$$

With $T = 100$ years, $\eta = 1.2$ and $\psi(c_0) = 6$, an event that reduces per-capita output by killing off $d\ln c = .01$ of the population has present value equal to 36 percent of current income. Letting $T = 1000$ —a catastrophe that could occur every thousand years, on average—the current value is about 4.5 percent of income. And of course the value is highly sensitive to the choice of r : a reduction in the discount rate from .06 to .04 raises the current value of avoiding such a catastrophe to 22 percent of current income.

Our results on the potential impact of uncertainty over the arrival time of harm from climate change and the distribution of its effects can have very large effects on the expected cost of climate change. The value of a loss of one percent of income brought about by catastrophic loss for 1 percent of the population that has a constant hazard of 1/100 per year has roughly 80 times the expected cost of a permanent loss of one percent of consumption that will occur for sure 100 years from now, even though both have the same expected reduction in aggregate income and the same expected arrival time. The implication is that uncertainty over the timing, magnitude and distribution of losses can have a very large effect on assessments of current cost.

Discounting the Returns on Climate Capital

One of the most controversial aspects of debates over climate change policy is the appropriate social discount rate to be applied to future damages. As we noted above, for any future value of incremental climate damage, a reduction in the interest rate used to value climate capital can greatly increase the costs that current generations should bear in order to avoid future

damages. At the extreme among economists, the *Stern Review*'s advocacy for a very low interest rate of .015 accounts for almost all of its severe recommendations. Behind the *Stern Review* recommendations is the notion that the welfare of future generations should be weighted equally with current ones, it being ethically repugnant to discount their welfare. Then the only source of a positive discount rate on real cash flows is the growth of consumption over time, because future generations are richer than we. And in the *Stern* recommendations even that is given little weight in reaching the desired result. Similarly, non-economists such as Archer (2009) have argued that economic analysis is itself ill-equipped to deal with intertemporal problems of a generation or more. Like *Stern*, Archer argues for effectively zero discounting because current action is a moral imperative.

The slowly ramping policy profiles offered by Nordhaus (2007) and others are based on higher discount rates that reflect historical long run returns on other types of capital. In contrast, while critiquing the analytical foundations of the *Stern* rates, Weitzman (2009) offers a “Dismal Theorem” based on the possibility of extreme catastrophes that drive consumption near zero and the marginal utility of consumption to the moon. Policies that can avoid such outcomes can have unbounded value under particular assumptions about the distribution of climate effects on c —they should have “fat tails”—and the rate at which marginal utility rises with reductions in income. While we think Weitzman's point is far-fetched, to us the more general point is that uncertainties about the distributions of climate damage and the payoffs from mitigation investments affect valuations. Climate policies that effectively insure against large downside risks needn't have large expected returns, so the typical market benchmarks might be inappropriate for investments in climate capital.

From an economic and empirical perspective the choice of a discount rate is not about the philosophical choice of the correct ethical weight to be applied to the welfare of our and other peoples' great-grandchildren, nor is it about the way we "should" discount marginal dollars of their income because they will be richer. As in all analyses that must balance costs and benefits, the issue is opportunity cost. The fact that costs and returns are so uncertain and widely spaced in time adds practical difficulties but not conceptual ones.

Consider a current project costing \$1 million that would reduce the impact of climate change 100 years from now. Assume that it would cost future generations \$20 million in real terms 100 years from now to mitigate or offset the impact of the resulting climate change. It is tempting to say that we should engage in the project if and only if we value giving \$1 to the current generation less than we value giving \$20 to the future generation. Hence, it would seem that the question of whether the mitigation project makes sense depends crucially on the relative values we place on the consumption of current and future generations. This is not correct.

Regardless of our preference for either the present generation or the future generation our choice regarding the mitigation project should be the same. Assume we wish to give the future generation the \$20M benefit they would derive from mitigating climate change today. Should policy dictate that the current generation undertake the project, forsaking \$1M in current consumption? The rate of return on this project is 3 percent, which is the solution for r in the equation $\$1,000,000 \times e^{100r} = \$20,000,000$. But if the market rate of interest is 6 percent, \$1m invested at the market rate of return would yield \$403 million in 100 years. It would be much better to have the current generation forego investment in climate mitigation and instead invest the \$1 million in other assets, like human capital or physical capital that provide much higher returns. Future generations would be better off as a result. Alternatively, it would take only

\$49,000 invested at 6 percent to provide the future generation with the \$20M needed to compensate them for the induced climate change. It would be far better to have the current generation invest \$49,000 in non-climate capital than to have them put \$1M into mitigating the cost of future climate change. Future generations would be no worse off and current generations would reduce their current costs by 95 percent. The point is that it is the market rate of return—not our attitudes toward future generations or our moral view of discounting—that determines the appropriate discount rate. To evaluate climate mitigation policy with a lower rate of return unnecessarily harms either current or future generations, or both.

As this example makes clear, it is appropriate to discount the costs and benefits of climate change policy at the market rate of return, precisely because the market rate of return measures the opportunity cost of such investments—returns available from investing the same amount in other real assets in the form of physical or human capital—so long as such opportunities exist. But what “market rate” should we use? At the low end we could benchmark by the risk free rate as represented by the returns on government bonds. Alternatively, we could benchmark against the much higher historical returns on risky investments such as physical capital or equities. Offered the opportunity to invest for the benefit of our great-grandchildren in 2110—who by any reasonable expectation will be much richer than we are¹³—would we opt for Treasury bills and an annual return of perhaps 3 percent when the historical equity premium consistently provides returns in the neighborhood of 6 to 8 percent?

Yet the fact that most of us would choose equities reflects an implicit but appropriate belief that those assets correctly gauge the opportunity cost for long-term financial investments,

¹³ At 1.5 percent annual growth, per capita income in 2110 will be about 4.5 times the current level. At 2 percent the multiple is 7.4. Growth rates in developing countries such as China or India are expected to be much higher.

including risk. But it is not obvious that the risks and returns on climate investments align with those on other physical assets or equities. If the returns on climate investments are uncorrelated with returns on the market portfolio, or if by eliminating calamitous harm to overall productivity and living standards they pay off exactly when other productive assets do not, then the appropriate rate of return and discount rate for climate projects would be much lower, even lower than the risk-free rate. Further, though the climate impacts of investments in climate capital are global, the risk properties of those effects, and hence their value, may differ greatly across the countries whose participation in global agreements is essential.

Expected Social Returns on Climate Capital

To illustrate these points, consider the standard asset pricing framework for valuing a current (time 0) investment that offers uncertain returns at some future date, call it F .¹⁴ Extending the usual asset valuation framework to social investments in climate capital, assume that the current generation can invest in λ units of a climate project, with current cost $K(\lambda)$ and marginal cost $k(\lambda) = K'(\lambda)$. The investment offers uncertain future returns of x per unit, where x may be interpreted as the project's future impact on GHG concentrations, or other measures that would mitigate climate impacts. The social planner's intertemporal problem is

$$(8) \quad \text{Max}_{\lambda} U = u(y_0 - K(\lambda), \xi_0) + \beta E \left[u(y_F(\lambda x), \xi_F(\lambda x)) \right]$$

The representative individual in (8) derives utility from income y and the state of the environment ξ , both of which can be affected by current climate investments. The factor $\beta < 1$ reflects pure time preference, and E is the expectations operator reflecting uncertainty over the

¹⁴ See Cochrane (2005) for a clear presentation of asset pricing and discounting issues.

joint distributions of y , ξ and x . We interpret this social valuation problem as country-specific, so that the distributions of outcomes may be quite different for, say, China than for the US.

The choice of investment in the climate project solves

$$(9) \quad \begin{aligned} k(\lambda) &= E[m_F X_F] \\ &= e^{-r_f} E(X_F) + \text{cov}(m_F, X_F) \end{aligned}$$

where r_f is the risk-free rate of return, m_F is the marginal rate of substitution between future and current consumption, and X_F is the future generation's value of the income and environmental payoffs on the investment:

$$(10) \quad X_F = (y'_F + \omega_F \xi'_F) x$$

Divide (10) by $k(\lambda)$ to obtain marginal returns per dollar invested ($R_F = X_F / k(\lambda)$) and solve for the required return on the environmental asset, which yields the familiar CAPM form for required expected returns on the investment, r_E :

$$(11) \quad \begin{aligned} r_E &= r_f - \text{cov}(m^F, R^F) \\ &= r_f - b_{m,R}(r_M - r_f) \\ &= r_M - (1 + b_{m,R})(r_M - r_f) \end{aligned}$$

In (11), r_M is the market rate of return on equities and $r_M - r_f = \text{var}(m)$ is the equity premium.

The term $b_{m,R} = \text{cov}(m, R) / \text{var}(m)$ is the environmental project's "beta." We have expressed b in terms of the covariance of R with m instead of the more traditional covariance with growth in income because of the presence of environment in welfare, u .

According to the third line in (11), the required expected return on the environmental asset will be smaller than the market rate so long as its market “beta” ($-b$) is smaller than 1.0. This has the usual risk-return interpretation—if the environmental asset offers greater payoff than the market when m (willingness to pay for environmental improvements) is high, then it reduces risk and can have a lower than market return. While this may seem likely, so $r_E < r_M$ can be appropriate, the first line of (11) offers a more aggressive point about risk and return for investments in climate projects—the expected return on an environmental project may fall below the risk-free rate if $\text{cov}(m, R) > 0$. As m typically falls with income, positive covariance of m and R is not relevant for most financial assets. But climate projects are alleged to have the potential of averting disasters, so they may payoff precisely when willingness to pay, m , is greatest. For example, if climate change may greatly reduce productivity and living standards, or cause widespread harm and death in some states of nature, then projects that avert such outcomes may be highly valued even if the payoff is rare—they have low expected return but high market value because they pay off when the mitigation of damage is most valuable.

In order to understand the forces shaping the appropriate discount rate for investments that mitigate climate change it is instructive to consider the variables that determine the marginal rate of substitution, m , and the return on climate mitigation, R . The marginal rate of substitution is determined by growth rate of consumption, which in turn is determined by the growth in productivity and various forms of human and physical capital. In addition, the growth in consumption may be affected by the degree of climate change, particularly in extreme cases where changes to the climate reduce productivity in various activities or cause large scale diversions of resources away from consumption. For modest levels of climate change this effect is unlikely to be important and the evolution of climate is likely to be only weakly related to the

growth in consumption—effectively the climate sector is a small part of the overall economy. However, for severe climate events consumption and climate outcomes could be highly correlated, with worse climate outcomes corresponding to lower levels of consumption.

There are at least four key stochastic drivers of the return on investments in climate mitigation. These include the rate of overall economic growth, the impact of GHG emissions on climate, the impact of climate change on the environment and human welfare, and the effectiveness of any given investment.

The rate of growth of overall economic activity will affect the return on investment in three ways. First, more rapid economic growth, particularly more rapid growth in developing countries like China and India, is likely to accelerate climate change and its effects. This is because higher incomes inevitably raise energy demands, and because economic growth is more energy intensive at low income levels. To the extent that the damages from climate change are convex in GHG emissions—which appears to be the operative assumption—this growth will raise the marginal value of investments in climate mitigation. Second, greater growth in wealth will increase the value placed on any increment of climate change by increasing the relative price of the environment, ω_F . Environmental quality is a normal good—willingness to pay rises with income—so growth in overall wealth will increase its value. A rising relative price of the environment raises R by increasing the price of the environmental output relative to other goods. Third, growth in overall activity will change the impact of climate on productivity. As the world gets richer, there is more output that can potentially be affected by climate change. On the other hand, much of current and future growth (particularly in developed countries) is likely to occur in information technology and other sectors where production is not highly dependent on environmental factors.

For rich countries, the marginal energy intensity of GDP is relatively low, so that the first factor linking R and economic growth is likely to be weak. Greater economic growth in these countries would have a modest effect on GHG emissions. In developed countries the second factor is likely to be the most important—greater economic growth is likely to raise willingness to pay for environmental improvements, ξ'_F .

For developing countries, the link between economic growth and the return on investment is likely to be strongly positive. More rapid economic growth will raise energy demand and, absent carbon pricing, this growth would be achieved through a large increase in use of carbon-based fuels. China's large endowment of easily accessible coal adds to this potential. Thus more rapid economic growth the developing world will accelerate GHG emissions and the effects of climate change. The growth in their incomes will also increase their willingness to pay so that the economic return to mitigation will rise even more. Given that much of their growth will be in consumer goods production and consumption, the energy intensity of their development (to the extent that it mirrors the historical experience of the developed world) will be high. All of these factors point to a strong positive link between willingness to pay and economic growth in the developing world.

The second stochastic factor, uncertainty over the impact of GHG emissions on the environment, induces a positive correlation between the marginal rate of substitution m and the return on investment, R . A larger impact of GHG emissions on the environment (holding other factors fixed) will tend to reduce consumption (by reducing productivity and/or diverting resources to climate mitigation) and at the same time imply a greater impact of GHG reduction on the environment (raising the marginal product of investment). It will also raise the willingness to pay for improvements in the environment by reducing the environmental

endowment. Thus, the greater the level of uncertainty over the impact of GHG on the environment, the more positive we would expect the correlation of m and R to be (implying a lower rate of discount). This will be particularly true of investments that seek to reduce GHG emissions (for which both links are important) but less true of investments that seek to mitigate the impact of climate change through other channels (for which only the channel is operative).

The third stochastic factor, the impact of the climate change on the quality of the environment also induces a positive correlation between consumption growth and the return on investment, R . The greater the impact of climate change on the environment, the greater will be the return on investment in climate change mitigation, for two reasons. First, any given reduction in climate change will translate into a bigger improvement in the environment. This would increase the return proportionately if willingness to pay per unit of environmental quality was unchanged. However, a greater impact of climate change on the quality of the environment will lower the environmental endowment and increase willingness to pay for any given increment to the environment. This will increase the return on investment even more. More environmental damage would likely reduce productivity and divert resources from consumption, so that a greater impact of climate change on the environment will induce a negative correlation between consumption and the return on investment and thus a positive correlation between m and R . Again, this indicates a lower than market rate of discount for climate change mitigation.

The final stochastic factor is how the physical return on investment for a given investment will vary with m . To model the return on investment, it is useful to think of investments in climate mitigation as investments in a capital stock, say S , so that the effect on the environment can be written as $F(S, Z)$, where Z represents other inputs used along with the stock. For example, S might represent investments in the capacity to capture carbon from the

atmosphere and Z would be the resources devoted to using that technology. With constant returns to scale this can be written as $Sf(z)$, where $z=Z/S$. In order to focus on the distinction between ex-ante and ex-post investments, we assume that z is chosen in the future, once the state of nature is known. We assume that markets are competitive so that Z will be chosen to maximize profits. Under these conditions, the optimized return, X , per unit of S is given by

$$(12) \quad X_t = \max v_t \theta_t f(z_t) - z_t.$$

Where v_t measures the market value of changes in the environment and θ_t represents the productivity of climate mitigation (stochastic factors two and three discussed above). A convenient form for $f(z)$ is the constant elasticity form $f(z_t) = Az_t^\gamma$, which yields

$$(13) \quad X_t \propto (v_t \theta_t)^{1/(1-\gamma)}.$$

The parameter γ measures the scalability of the investment project. Some investments such as reducing current GHG emissions are not scalable in that they cannot be adjusted once the values of v and θ are realized. Other, investments, such as investments in developing new technologies or investments in the capacity to remove carbon from the atmosphere or mitigate its effects are scalable in that while they may require investments today their usage can be adjusted based on the future demand for climate mitigation. A perfectly scalable technology, $\gamma=1$, would limit the marginal cost of environmental change, $v_t \theta_t = 1/A$, which would effectively truncate the distribution of the marginal cost of environmental damage. Such a technology would provide a great deal of insurance by eliminating the worst states of nature. However, even technologies that are not perfectly scalable can have substantial value. When $\gamma>0$, X is more sensitive to

changes in the value of the environment and the impact of climate change on the environment (with an elasticity of $1/(1-\gamma)$). This enhances the positive correlation between m and R leading to an even lower implied rate of discount for such projects. The interpretation is that more scalable technologies are more attractive because they provide additional insurance—they are deployable as needed. The magnitude of this advantage depends on the uncertainty about θ and v . The greater the level of uncertainty, the greater is the (current) value of ex-post scalability.

This is our earlier point about the value of scalable technologies—research and development investments in mitigation technologies that can be deployed in large scale in the event that damages are large can offer important insurance against looming catastrophe. Such projects should not be heavily discounted. This is, we think, the less extreme and more relevant implication of Weitzman’s “Dismal Theorem” analysis.

Conflicting Valuations

This analysis also reflects the types of conflicts that can arise in international negotiations over climate policy. The fact that climate is a global public good means that near-harmonized participation by major players is important. Yet the covariance of payoffs and value are likely to be substantially different for different countries. For developed countries rapid world-wide growth may cause widespread environmental harm, and willingness to pay in such states may be high. But these “bad” states of nature for developed countries are exactly the good states for China and India, whose rising incomes cause falling m when environmental damages are large.

More generally, uncertainty over the rate of growth of output driven by forces other than climate tends to generate a positive correlation between returns and economic growth. Greater

world-wide growth means more rapid climate change (particularly for developing countries) and more rapid growth in the willingness to pay for environmental improvement. On the other hand, uncertainty about the impact of GHG on climate change and uncertainty about the impact of climate change on the quality of the environment and productivity generates a negative correlation between returns and economic growth (a positive correlation between returns and m). Higher than expected environmental damage lowers economic growth (by diverting resources and reducing productivity) and raises both the return and willingness to pay for environmental improvement. This effect is particularly important for large or catastrophic changes in the environment where the effect on marginal products and welfare are both likely to be large. The possibility of such events makes investments climate change mitigation attractive, particularly investments in scalable technologies.

References

- Archer, David, *Global Warming: Understanding the Forecast*, Blackwell Publishing, Ltd., 2007.
- Archer, David, *The Long Thaw*, Princeton University Press, Princeton, N.J., 2009.
- Cochrane, John, *Asset Pricing*, Princeton University Press, Princeton, N.J., 2005.
- Dyson, Freeman, "The Question of Global Warming", *The New York Review of Books*, June 12, 2008.
- Hall, Robert E. and Charles I. Jones, "The Value of Life and the Rise in Health Spending", *Quarterly Journal of Economics*, 122 (2007), pp 39-72
- Hotelling, Harold, "The Economics of Exhaustible Resources", *Journal of Political Economy*, April, 1931, pp 137-175.
- Murphy, Kevin M. and Robert H. Topel, "The Value of Health and Longevity", *Journal of Political Economy*, October, 2006, pp 871-904.
- Nordhaus, William, "A Review of the Stern Review on the Economics of Climate Change", *Journal of Economic Literature* 45 (3), 2007, 686-702.
- Nordhaus, William, *The Challenge of Global Warming: Economic Models and Environmental Policy*, Yale University, 2007.
- Nordhaus, William, *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, 2008.
- Stern, Nicholas, et. Al., *The Stern Review on the Economics of Climate Change*, U.K. Treasury, 2006.
- Weitzman, Martin, "The Stern Review of the Economics of Climate Change", *Journal of Economic Literature* 45 (3), 2007.
- Weitzman, Martin, "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *Review of Economics and Statistics*, February, 2009, pp 1-19.