6 Climate Change

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Scoping the problem

The Intergovernmental Panel on Climate Change (IPCC, 2001) offered perhaps the most efficient presentation of the climate change problem with its "burning ember" diagram; it is replicated here as Figure 6.1.

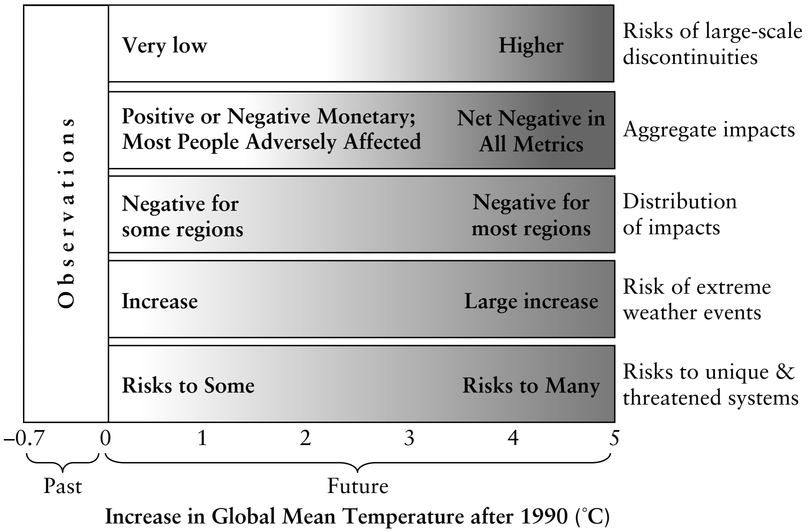

Figure 6.1. Sources of concern and shaded indications of vulnerability

Source: Figure 19-8-1 in IPCC (2001). Relative levels of vulnerability along five "Lines of Evidence" or "Sources of Concerned" and their sensitivity to increases in global mean temperature were assessed based on the literature available through the middle of 2000. Low vulnerability was indicated by a white or very pale yellow coloration, here indicated by light grey. High vulnerability was highlighted by red coloration, here indicated by very dark grey; and intermediate vulnerabilities by various shades of yellow and orange.

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The diagram identifies five "Lines of Evidence" with color-coded indicators of economic, social, and natural vulnerabilities. Two are essentially economic indicators of aggregate impacts at the global and regional levels. They are dominated by estimates of the economic damage of climate impacts in market-based sectors such as real estate, agricultural, and energy, and they increase with the global mean temperature. They include, to some degree, evaluations of how various nations and even communities within nations might adapt to climate-related stress driven by higher temperatures as well as the cost of undertaking those adaptations.

In its recently released Fourth Assessment Report (IPCC, 2007), the IPCC concluded that new knowledge supports moving the thresholds of color change indicating increasing risk in the embers to the left – toward lower temperature ranges. It follows that potentially significant impacts are looming in the nearer term. Table 6.1 replicates table 6.1 in Stern, *et al.* (2006). Based on background work reported in Warren, *et al.* (2006), it adds texture and content to the moving embers, and it provides evidence that the new IPCC conclusion is an appropriate interpretation of how the science is evolving. Notice, in particular, how Table 6.1 shows clearly that climate impacts are likely to be felt unevenly across the globe. Notice, as well, that the remaining rows in Figure 6.1 focus attention on ecosystems (and other non-market risks), as well as two potentially more significant areas of concern: "Risks from Future Large-Scale Discontinuities" and "Risks from Extreme Weather Events"; both are also reflected in Table 6.1.

Scoping some solutions

Even though the climate problem will not be "solved," it is, though, possible to describe responses that could at least partially ameliorate additional damages. Estimates of economic cost are, of course, key components of such descriptions. While economists disagree on what the future might hold, they agree that "the social cost of carbon" is a useful measure with which to summarize both the size of the problem and efficient responses to the associated risks – i.e., the damage caused over time by releasing an additional tonne of carbon in the atmosphere discounted back to the year of its emission. The social cost of carbon therefore represents the "marginal cost" of emissions. Alternatively, it

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Table 6.1. ***Highlights of possible climate effects***

A summary of the recent science on climate impacts calibrated by increases in global mean temperature for major sectors of interest.

Temp rise (°C)	Water	Food	Health	Land	Environment	Abrupt and Large-Scale Impacts
1°C	Small glaciers in the Andes disappear completely, threatening water supplies for 50 million people	Modest increases in cereal yields in temperate regions	At least 300,000 people each year die from climate-related diseases (predominantly diarrhoea, malaria, and malnutrition) Reduction in winter mortality in higher latitudes (Northern Europe, USA)	Permafrost thawing damages buildings and roads in parts of Canada and Russia	At least 10% of land species facing extinction (according to one estimate) 80% bleaching of coral reefs, including Great Barrier Reef	Atlantic Thermohaline Circulation starts to weaken
2°C	Potentially 20–30% decrease in water availability in some vulnerable regions, e.g.	Sharp declines in crop yield in tropical regions (5–10% in Africa)	40–60 million more people exposed to malaria in Africa	Up to 10 million more people affected by coastal flooding each year	15–40% of species facing extinction (according to one estimate) High risk of extinction of	Potential for Greenland Ice Sheet to begin melting irreversibly, accelerating sea

Table 6.1. *(cont.)*

Temp rise (°C)	Water	Food	Health	Land	Environment	Abrupt and Large-Scale Impacts
	Southern Africa and Mediterranean				Arctic species, including polar bear and caribou	level rise and committing world to an eventual 7 m sea level rise
3°C	In Southern Europe, serious droughts occur once every 10 years 1–4 billion more people suffer water shortages, while 1–5 billion gain water, which may increase flood risk	150–550 additional millions at risk of hunger (if carbon fertilisation weak) Agricultural yields in higher latitudes likely to peak	1–3 million more people die from malnutrition (if carbon fertilisation weak)	1–170 million more people affected by coastal flooding each year	20–50% of species facing extinction (according to one estimate), including 25–60% mammals, 30–40% birds and 15–70% butterflies in South Africa Onset of Amazon forest collapse (some models only)	Rising risk of abrupt changes to atmospheric circulations, e.g. the monsoon Rising risk of collapse of West Antarctic Ice Sheet Rising risk of collapse of Atlantic Thermohaline Circulation
4°C	Potentially 30–50% decrease in	Agricultural yields decline by 15–	Up to 80 million more people	7–300 million more people affected by	Loss of around half Arctic tundra	

	water availability in Southern Africa and Mediterranean	35% in Africa, and entire regions out of production (e.g. parts of Australia)	exposed to malaria in Africa	coastal flooding each year	Around half of all the world's nature reserves cannot fulfill objectives
5°C	Possible disappearance of large glaciers in Himalayas, affecting one-quarter of China's population and hundreds of millions in India	Continued increase in ocean acidity seriously disrupting marine ecosystems and possibly fish stocks		Sea level rise threatens small islands, low-living coastal areas (Florida) and major world cities such as New York, London, and Tokyo	
More than 5°C	The latest science suggests that the Earth's average temperature will rise by even more than 5 or 6°C if emissions continue to grow and positive feedbacks amplify the warming effect of greenhouse gases (e.g. release of carbon dioxide from soils or methane from permafrost). This level of global temperature rise would be equivalent to the amount of warming that occurred between the last ice age and today – and is likely to lead to major disruption and large-scale movement of population. Such "socially contingent" effects could be catastrophic, but are currently very hard to capture with current models as temperatures would be so far outside human experience.				

Source: Stern et al. (2006), ch. 3.

represents the "marginal benefit" of unit of carbon emissions reduction, and it can serve as an estimate of the appropriate carbon tax.

More than 100 estimates of the social cost of carbon currently available in the published literature were surveyed by Tol (2005). The median estimate is $13 per tonne of carbon. The mean is $43 per tonne, and the upper end of the range lies above $350 per tonne of carbon. How should all of this disagreement be interpreted? Richard Tol, the economist who prepared the survey, read the range to mean that roughly $50 per tonne should be interpreted as representative of the highest reasonable "best" estimate of the social cost of carbon. Thomas Downing (2005), a geographer from the Stockholm Environment Institute, looked through the lens of his enormous experience in developing countries where changes in climate produce enormous displacement and other transitional effects that cannot be quantified in terms of currency. He read the data to mean that $50 per tonne should be interpreted as representative of the lowest reasonable estimate of the true social cost of carbon.

But why is the range so large? Which of the "Lines of Evidence" do the estimates include, and which do they miss? What combinations of underlying factors produce low or high estimates of social cost? Answers to these questions can be enormously revealing. The choice of discount rate and the incorporation of equity weights are extremely important, and both lie within the purview of decision-makers. High (low) discount rates sustain low (high) estimates because future damages become insignificant (are exaggerated). Meanwhile, strong (weak) equity weighting across the globe support high (low) estimates because poor developing countries are most vulnerable.

It turns out, however, that several scientific parameters over which decision-makers have no discretion are even more important in explaining the variability in the estimates. Climate sensitivity (the increase in global mean temperature that would result from a doubling of greenhouse gas concentrations from pre-industrial levels) is the largest source of variation; see Hope (2006). Valuation of non-market impacts ranks second. In fact, it is possible to derive high estimates for the social cost of carbon even if you assume low discount rates and almost no equity weighting. All that is required is the assumption that the climate sensitivity lies at the high range of the latest range of estimates. Andronova and Schlesinger (2001) find that the historical record could easily be explained with climate sensitivities as high as

9°C (even though the TAR reported an upper bound of 5.5°C); both admit that a sensitivity below 1.5°C is impossible. Moreover, none of the estimates included in the survey include *any* internally consistent reflection of economic costs of "Risks from Extreme Climate Events" or "Risks from Future Large-Scale Discontinuities."

To understand the significance of these omissions, consider the possibility that the Atlantic Thermohaline Circulation might weaken significantly or even suddenly collapse. The climate research community has not yet prepared comprehensive portraits of the implications of such a collapse, but there is consensus in the view that impacts would be abrupt (occurring within a decade or two) and felt across the globe (i.e., not just in Europe). It is, as well, widely held that finding out what would happen is not really an experiment that should be conducted on our only planet (since the collapse would likely be irreversible). Schlesinger, *et al.* (2006) put the chance of collapse at 50% if the global mean temperature were to climb by another 2°C beyond 1990 levels. Put another way, Yohe, *et al.* (2006c) show a 45% chance of collapse by 2105 along a "middle of the road" emissions scenario across the full range of climate sensitivities. Imposing a *global policy* targeted at a $50 per tonne social cost of carbon would reduce that likelihood to 30% if it were initiated immediately; but only to 40% if the policy intervention were delayed by 30 years.

To be clear, adding on a static $50 per tonne carbon tax (adding something like $5 to the price of a barrel of oil) would not do the trick over the long term. Watkiss (2005) has shown that the social cost of carbon, and thus the appropriate tax, should increase in real terms by 2% or 3% per year – approximately the endogenously determined real rate of interest. This is the critical component of the policy; that is, *it is the persistent and predictable ratcheting-up of the effective price of carbon* that would give the policy traction at all.

Evaluating solutions – imposing a $50 per tonne carbon tax (or its equivalent)

What else can be said about a $50 per tonne tax on carbon? Since it lies close to the mean of the published estimates in Tol's survey, it is certain that its estimated benefits would exceed its estimated costs for some combinations of discount rate, equity weighting, and scientific variables. Low discounting, high equity weighting, and high climate

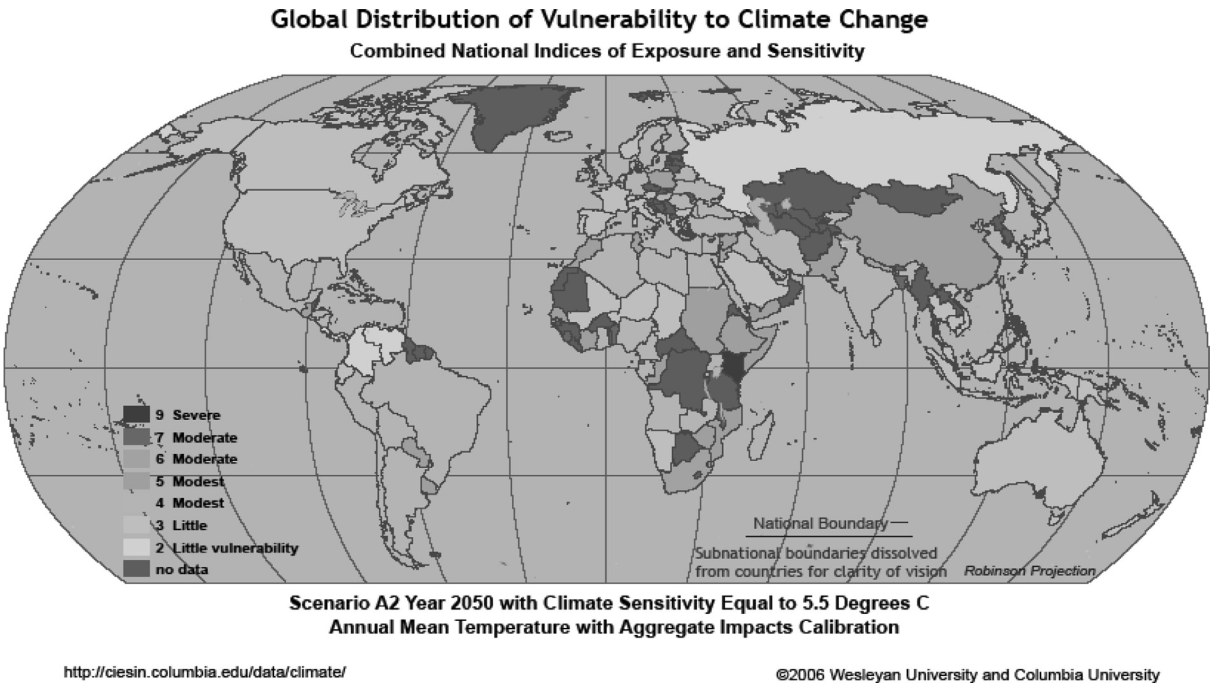

Figure 6.2. Geographical distribution of vulnerability in 2050 with a climate sensitivity of 5.5°C.

Source: Yohe, et al. (2006a) and (2006b).

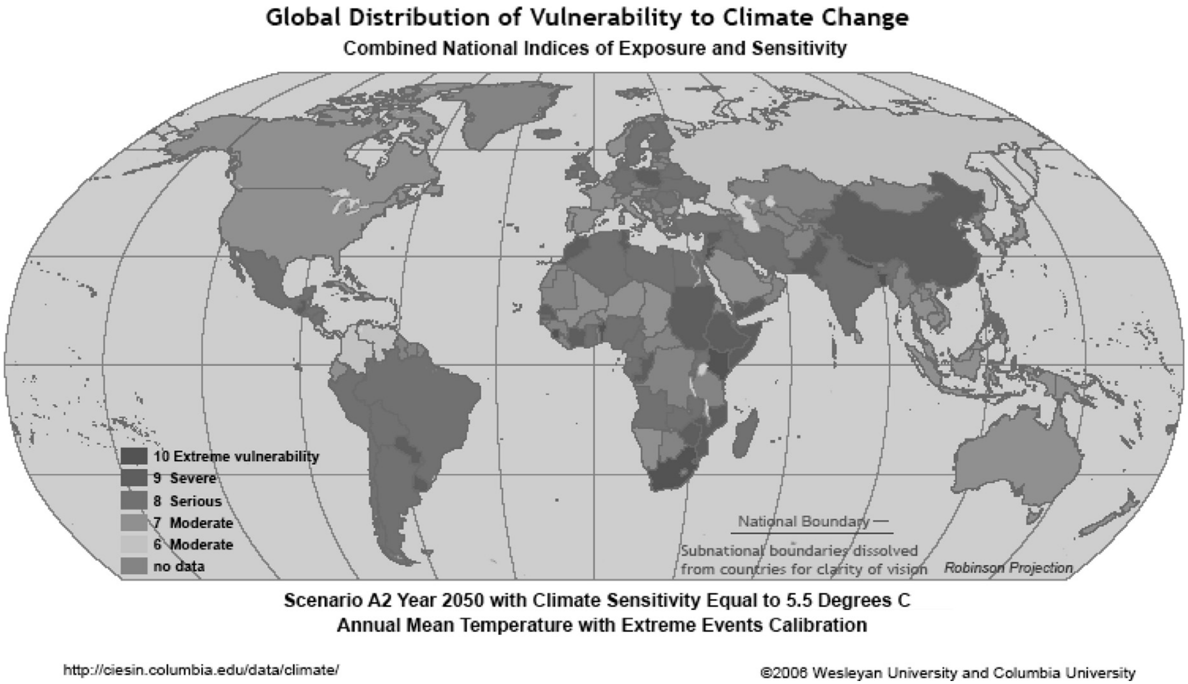

Figure 6.3. Geographical distribution of vulnerability in 2050 with a climate sensitivity of 5.5°C.

Source: Yohe, et al. (2006a) and (2006b).

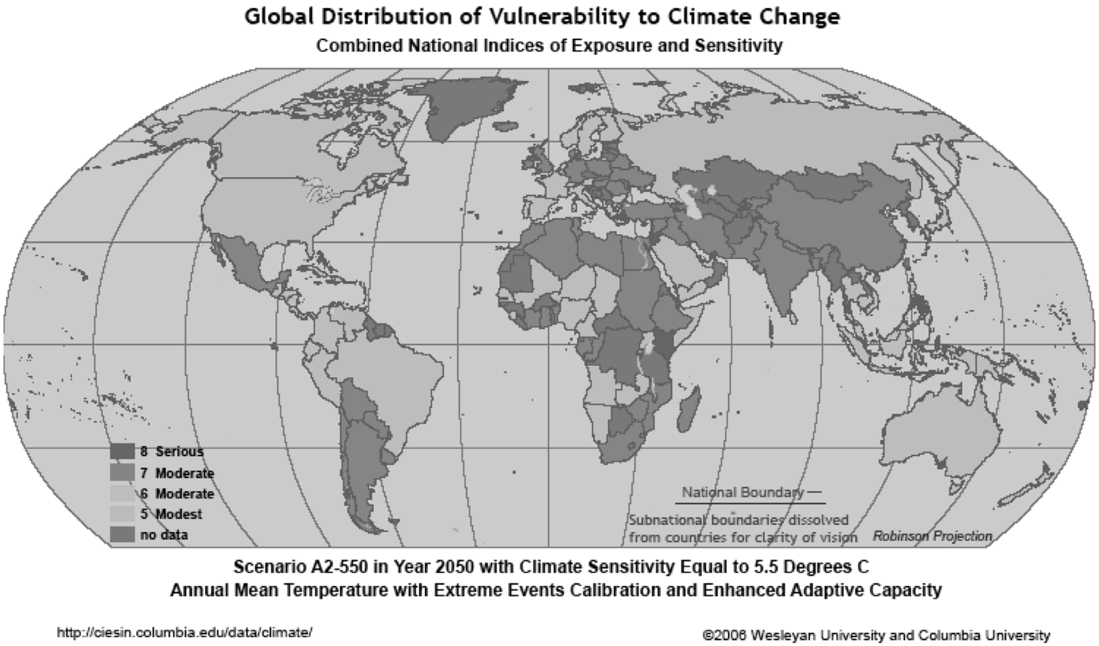

Figure 6.4. Geographical distribution of vulnerability in 2050 with a climate sensitivity of 5.5°C, enhanced adaptive capacity alone and combined with concentrations of greenhouse gases limited to 550 ppm in carbon dioxide equivalents

Source: Yohe, et al. (2006a) and (2006b).

sensitivities would do the trick. Of course, costs would dominate benefits for other combinations characterized by more aggressive discounting, less concern about equity, and low climate sensitivities.

Given the wide range of impacts that are not included in the calculations of benefits, however, a strong case can be made that we simply do not know enough to be at all confident in comparisons based on incomplete statistics; see Yohe (2004) and Tol (2003). For present purposes, these shortcomings mean that any evaluation of the benefits of a $50 per tonne tax will simply miss many of the most important benefits simply because they have not been quantified in terms of currency.

Table 6.2 tries to offer some insight into the scope of these omitted benefits for five different cases after it records gross and net (available partial estimates of the economic value of damages avoided deducted from gross costs) in Columns (1) and (2). Column (3) reports net costs as a fraction of discounted GDP through 2105, and it also indicates abatement costs for the first 10 years (when avoided damages are likely to be minimal) as a percentage of then current GDP. Evidence-constrained benefit–cost ratios are reported in Column (4). All of these estimates are derived from the baseline emissions scenario generated by the DICE integrated assessment model and described by Nordhaus and Boyer (2000).

Insights into omitted benefits are recorded in Columns (5) through (7). They are derived from Arnell, *et al.* (2002) for alternative evaluative metrics that track three measures of risk of climate change: millions at risk of hunger, millions at risk of water scarcity, and millions at risk of coastal flooding. Their work has shown that limiting the increase of global mean temperature to 1.2°C (above the average of the last third of the twentieth century) rather than allowing an unregulated 2.9°C warming through 2080 would remove 43 million, 2,070 million, and 74 million people from those risks, respectively, if the climate sensitivity were something like 3°C. Columns (5) through (7), in fact, report the per capita expense of achieving these reductions.

Case 1, described in the first row of Table 6.2, considers implementing the $50 per tonne tax in 2006 and reports the various evaluative metrics under the assumption that the climate sensitivity is, in fact, 3°C. The high (low) discount case sets the pure rate of time preference at 3% (0%) so that the Ramsey discount rate falls over time from near 5% (2%) to something closer to 4% (1%) by 2105. Notice that the per-capita costs of reduced risk of hunger, water scarcity, and coastal

Table 6.2. *Comparative statistics for five alternative cases*
Calculations indicating costs and benefits for alternative policy approaches designed to reduce greenhouse gas emissions over the near term into the more distant future.

	(1)[a] Cost present value through 2105	(2)[b] Net cost present value through 2100	(3)[c] Net cost %GDP through 2100 (first 10 yrs)	(4)[d] Lower bound for the B/C ratio	(5)[e] Risk of hunger (in 2080)	(6)[f] Risk of water scarcity (in 2080)	(7)[g] Risk of coastal flooding (in 2080)
(1) Case 1 (3°)							
50/tonne							
Begin in 2006							
High discount[h]	$12.73	$0.46	0.04%	>> 0.96	$17,692	$222	$6,216
Low discount[i]	$110.81	$0.76	0.02% (0.22%)	>> 0.99	$29,231	$367	$10,270
(2) Case 2 (1.5°)							
$5/tonne							
Begin in 2006							
High discount[h]	$0.22	$0.44	0.04%	>> 2.00	$24,444	$379	$27,500
Low discount[i]	$2.22	$0.20	0.00% (0.00%)	>> 0.99	$1,111	$17	$1,250

(3) Case 3 (5.5°)							
$75/tonne Begin in 2006							
High discount[h]	$19.23	$0.74	0.06%	>> 0.96	$15,417	$266	$9,737
Low discount[i]	$141.52	$1.07	0.03%	>> 0.99	$22,292	$385	$14,079
			(0.47%)				
(4) Case 4 (3°)							
$100/tonne Begin in 2016							
High discount[h]	$16.14	$0.59	0.05%	>> 0.96	$22,692	$285	$7,973
Low discount[i]	$129.43	$0.95	0.02%	>> 0.99	$36,538	$459	$12,838
			(0.58%)				
(5) Case 5 (1.5°)							
$8/tonne Begin in 2016							
High discount[h]	$0.73	$0.44	0.04%	>> 1.91	$24,444	$204	$27,500
Low discount[i]	$2.33	$0.02	0.00%	>> 0.99	$1,111	$9	$1,250
			(0.00%)				

Notes:

[a] Derived from DICE (Nordhaus and Boyer, 2000) in trillions of dollars (1995$).

Table 6.2 (cont.)

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[b] Net costs derived from DICE (Nordhaus and Boyer, 2000); includes estimates of climate damages avoided with little recognition of damage associated with climate-related extreme events and valuation of unique systems. Abrupt climate change is included in terms of an estimate of the willingness to pay to avoid such events.

[c] Net costs as a percentage of discounted GDP through 2105; in parenthesis, abatement costs during the first ten years of implementation (i.e., through 2016 for cases 1, 2 and 3 but from 2016 until 2026 for cases 4 and 5).

[d] Benefits computed by comparing columns (1) and (2); the ratio uses column (1) as a denominator. Since so many benefits of climate change have not yet been quantified (and may never really be quantified), these ratios represent lower bounds of the appropriate ratios since the numerator could be much larger.

[e] Derived from Arnell, *et al.* (2002) estimates of number of people removed from risk. Options 1 and 4 reduce exposure from 69 million to 43 million in 2080; Options 2 and 5, from 61 million to 42 million; and Option 3, from 91 to 43 million.

[f] Derived from Arnell, *et al.* (2002) estimates of number of people removed from risk. Options 1 and 4 reduce exposure from 2.83 billion to 760 million in 2080; Options 2 and 5, from 1.92 billion to 760 million; and Option 3, from 3.44 billion to 760 million.

[g] Derived from Arnell, *et al.* (2002) estimates of number of people removed from risk. Options 1 and 4 reduce exposure from 79 million to 5 million in 2080; Options 2 and 5, from 21 million to 5 million; and Option 3, from 81 to 5 million.

[h] High discounting set the pure rate of time preference for Ramsey discounting equal to 3%; with DICE employing a logarithmic utility function, this amounts to real discount rates between something close to 5% and, later in the century, 4%.

[i] Low discounting set the pure rate of time preference for Ramsey discounting equal to 0%; with DICE employing a logarithmic utility function, this amounts to real discount rates between something close to 2% and, later in the century, 1%.

flooding are all less than $30,000 in discounted terms – a level that compares favorably to estimates of $300,000 to $104 million per life saved from existing Occupational, Safety and Health Administration (OSHA), National Highway Traffic Safety Administration (NHTSA), and the Environmental Protection Agency (EPA) regulations on everything from passive restraints in automobiles to asbestos exposure; see Viscusi (1996).

Since so much has been made of uncertainty in our estimates of climate sensitivity, Cases (2) and (3) of Table 6.2 record the results of repeating the exercise for 1.5°C and 5.5°C, respectively. In both cases, the initial tax is adjusted to achieve 1.2°C temperature increase benchmark in 2080 so that the Arnell, *et al.* (2002) estimates of risk reduction can be employed; estimates for the unregulated baselines were adjusted, as well, from their work. Notice that the initial tax and all aggregate cost metrics are higher for the higher sensitivity and lower for the lower sensitivity. The costs of reduced risk are lower for the lower climate sensitivity, but they are also lower for the higher sensitivity; this is because high climate sensitivities exaggerate the risk associated with the unregulated benchmark scenario so that the benefit is enlarged.

And what if implementation of the policy were delayed by 10 years? Cases (4) and (5) indicate that costs would be uniformly higher (by as much as 50%) for climate sensitivities equal to 3°C and 1.5°C. For a sensitivity of 5°C, however, the news is even worse; the 10-year delay in implementation means that the 1.2 degree warming benchmark in 2080 becomes unachievable with *any economically palatable climate policy.*

Results

Table 6.2 presents some of the economic consequences of imposing a tax on the carbon content of fossil fuel. The specific policy offered in Case 1 would charge $50 per tonne beginning in 2006 and allow this charge to increase at the rate of interest through 2105. Alternatives were offered, but they were contingent on climate sensitivity and the date of implementation. All would effectively limit the increase in temperature through 2080 to 1.2°C; the version described in Case 1 for a climate sensitivity of 3°C would restrict atmospheric concentrations of greenhouse gases to 550 ppm in carbon dioxide equivalents.

In addition to economically quantified benefits that never fell below 90% of abatement cost for any case examined, implementing any of the alternatives would produce a 33% reduction in the likelihood of a collapse of the Atlantic thermohaline circulation. Reductions in risk to hunger, water scarcity, and coastal flooding in 2080 never rose above $30,000 per person.

These benefits must, of course, be viewed in the context of opportunity cost – investments in progress toward the other challenges identified by the Copenhagen Consensus. How, in particular, would climate policy participate as part of a portfolio of initiatives designed to effectively spend $75 billion on global welfare? Yohe, et al. (2006a and 2006b) have shown that the benefits of climate policy are seen most strikingly in countries where the other challenges are largest – the developing countries of Africa, southern Asia, and South America. There is synergy across approaches to these challenges that should be exploited. Moreover, many of the goals embodied in the other challenges are, in fact, underlying determinants of adaptive and mitigative capacities; see Yohe and Tol (2002) and Yohe (2001), for example. Progress in overcoming these challenges will make climate policy more effective.

Should climate policy be part of the Copenhagen Consensus portfolio of responses? Declining the opportunity to respond to the climate change challenge would make achieving other goals more difficult; accepting the challenge as described here would offer the chance of exploiting significant synergies. At what cost? Since the carbon tax policy could be self-sufficient (e.g., by allocating some tax revenue to administering, negotiating and monitoring or by imposing a very modest Tobin tax on carbon permit transactions under a cap and trade system) the question is how much to deduct from the Copenhagen Consensus bottom line. The economic costs reported in Column (1) are *not* the appropriate charges. These are economic costs, but they are not administrative costs. To compute the latter, suppose that donations to the $100 billion budget were to decline in proportion to abatement cost expressed in terms of a percentage of discounted global GDP. These are the values reported in Column (3) of Table 6.2, and none of those values exceeds 1% even for a climate sensitivity of 5.5°C. Taking the range seriously, the $50 per tonne carbon tax proposal advanced here would cost the Copenhagen Consensus bottom line no more than $1 billion regardless of the discount rate applied. In short, devoting no more than 1% of the Consensus budget would help assure that the other $99 billion does not "swim upstream" against climate damages. Seems like too good a deal to refuse.

Caveats, context and design

It is important, in thinking about how to respond to the risks posed by climate change, to recognize that setting near-term policy can be an exercise in determining the appropriate short-term incentives for carbon-saving investments and energy conservation rather than an exercise in "solving" the climate problem once and for all. The options described above are all extended 100 years into the future, and their specifications depend, to some degree, on the discount rate (a parameter over which decision-makers have some authority). They also depend, to a large degree, on climate sensitivity. This is one of many parameters over which only Mother Nature has purview, and she has not been particularly forthcoming about what value is most appropriate. Given that she is likely to remain "tight-lipped" about climate sensitivity and other climate system details for a long time, it is perhaps desirable to step out from under the burden of trying to address the unmanageable long-term problem. Perhaps, instead, we should agree to confront the more tractable near-term question of what to do over the next few decades while still preserving our ability to make progress toward an ultimate response to climate risk.

A good answer to the "What to do now?" question is simple to describe. Design something that will (1) discourage long-term investments in energy, transportation, and construction that would lock in high carbon intensities for decades to come, and (2) encourage development of alternative energy sources, carbon sequestration technologies and efficiency, while (3) not causing enormous economic harm (and thereby impeding our ability to make progress in overcoming the other challenges discussed in the Copenhagen Consensus project). Done correctly, such an approach holds the promise of reducing the expected discounted cost of meeting whatever climate policy goal turns out to be appropriate, and so it holds the promise of complementing investments designed to confront those challenges.

As an example of how these short-term objectives might be achieved, one might consider what it would take to make it economically attractive to run existing natural gas-fired electric generators more intensively and coal-fired generators correspondingly less intensively. Why? Because gas-fired generators emit only about half as much carbon per unit of electricity. Natural gas is considerably more expensive than coal, however, so it would take a substantial carbon price to inspire such a change – about $100 per tonne of carbon given current fuel price expectations. This, of course, is larger than the $50 proposal discussed above.

On the other hand, consider pending investments to add new generating capacity across the United States (and the entire world, for that matter) over the next few decades. Much of this capacity is currently planned as conventional coal-fired technology. What would it take, in terms of carbon price, to make it economic to install new gas-fired capacity instead? On current gas price expectations, a carbon price of about $20 per tonne would be sufficient to make new gas-fired generators as economical as new coal-fired plants based on the present value of fixed and variable costs and limited uncertainty. Several confounding economic factors (such as greater price volatility) add uncertainty, though, so it may be necessary to set an initial carbon price somewhere above $20 per tonne to achieve the desired economic equivalence (but something lower than $50 per tonne would suffice). Lower costs involved in building a new gas plant can compensate for a large difference in fuel cost.

To make the full step to near zero carbon technologies (e.g., carbon capture and sequestration) would require a somewhat higher price – also estimated at around $100 per tonne of carbon by several sources and included in Pacala and Socolow (2004) as one possible "wedge" of emissions reduction. Meanwhile, a $100 per tonne of carbon tax has been identified as the level for which current sequestration technologies might become economically efficient in many places. McCarl and Sands (2007) estimate that annual terrestrial offsets could total between 1 billion tonnes of carbon dioxide between 2010 and 2035 if a $100 per tonne value were assigned to carbon. Some of the detail behind estimates of this sort has been offered by Antle, *et al.* (2007). They show carbon sequestration supply curves for conservation tillage in the agricultural heartland of the United States beginning at carbon dioxide prices that range between $20 and $40 per tonne and reach capacity thresholds between $100 and $200 per tonne.

Bringing these technologies up to scale would take more than a decade, of course, and large investment would be based on the same type of present value calculation outlined above. It is here where the

Hotelling rule helps. Since power generators and sequestration projects last 30 to 40 years or more, increasing the carbon price at the rate of interest can make CCS technologies attractive in the present value calculation even if it does not reach the economic "tipping point" for some time. The $50 per tonne charge in 2007 proposed above would, for example, reach $100 just around 2021 (at a 5% interest rate), and that should be sufficient to affect even the retrofitting switch in most places and inspire appropriate development of enhanced sequestration techniques.

A carbon tax would not, of course, provide any incentive to sequester carbon by itself; doing that would require a targeted use of some of the tax revenue. Yohe (1989) describes how some of the revenue might be used to "buy back" carbon that was removed from the end of the effluent stream at a price that equals the tax applied at the beginning. Doing so would mean that the marginal cost of bringing in the last tonne would equal the marginal cost of taking it out – an efficiency criterion that "closes the loop."

And what about policy design? Cap and trade systems have become the stock in trade of many who try to advocate climate policy, but this preference may be based on little more than an allergic reaction to the use of the word "tax." Since concentrations depend on cumulative emissions over long periods of time, there is no Weitzman (1974) reason to favor a policy that would fix annual emissions. Yohe (1992) noted, more specifically, that fixing total emissions of any pollutant only makes sense if period-to-period variability around a targeted mean (that would improve economic efficiency) would unnecessarily increase expected social costs; and he argued that this is clearly not the case for carbon emissions. In addition, Newell, *et al.* (2005), among others, have expressed concerns that the prices which clear cap and trade permit markets can be volatile. Volatility has certainly been the hallmark of the sulfur permit markets in the United States and the nascent carbon markets of the European Union. Pizer (2002) responded to the threat of incapacitating volatility by proposing "safety valve" limits on the price of permits. Others have argued that volatility can be diminished by appropriate banking provisions. The fundamental problem with either solution is that appropriate climate policy requires a clear signal that carbon will always be more expensive next year than it is today. Even a modest amount of volatility can obscure that signal.

On other hand, a tax, increasing at the rate of interest à la Hotelling, would produce a persistent and predictable increase in the cost of using carbon that would inspire cost-reducing innovation and fuel switching in the transportation, building, and energy supply sectors of our economy. If carbon were taxed at the point it entered an economy (a couple of thousand sources in the United States, for example, as opposed to millions of end-users), then it would be dispersed appropriately throughout the economy with relative prices of thousands of goods changing in proportion to the underlying carbon intensities. Moreover, it would generate revenue. A $60 per tonne of carbon dioxide tax would, for example, generate something like $90 billion in tax revenue in the United States in 2007 if it were paid on every tonne of carbon embodied in every unit of fossil fuel consumed. This is revenue that could be used to offset the regressive nature of the carbon tax itself, by underwriting tax credits for citizens with taxable incomes below a specified level. The substitution effect would still apply, of course, so carbon conservation could be expected even from the beneficiaries of the credits. Tax revenue could also be used to reduce other distortional taxes. It could even be used to fund research into alternative energy sources.

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