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Stabilizing the global climate: A simple and robust benefit cost analysis

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Abstract

Most models of optimal climate change policy are complex and opaque. In this paper, it is argued that the convexity of climate damage and mitigation cost function provides a basis for the derivation of simple and robust estimates of optimal stabilization targets and carbon prices. For all but a few extreme assumptions, the optimal carbon price is between \$40 and \$75. Similarly, for a wide range of parameter values the optimal target is between 425 ppm and 475 ppm. In all simulations, the total cost of mitigation is below 5 per cent of income, and in most cases substantially below.

Stabilizing the global climate: A simple and robust benefit cost analysis

Climate change has been described as ‘the greatest market failure the world has seen’ (Stern 2007). It is also among the most complex and difficult issues facing both policymakers and the public. An indication of the complexity of the issue may be seen by considering the Assessment Reports of the Intergovernmental Panel on Climate Change (2007a, 2007b, 2007c),. Each Report contains the findings of Three Working Groups, on Physical Science, Impacts and Mitigation, each of which contains around 1000 pages of text. These volumes do not contain original research, but aim to synthesize the most relevant findings of the thousands of journal articles, books and reports listed in their bibliographies.

Proceeding to the literature, the problems faced by anyone seeking to understand the problem only intensify. The crucial issues are typically addressed using large-scale models each of which is the product of many researcher-years of effort, and each of which would require an intensive effort to understand.

The work of the IPCC is sufficient to allow some firm conclusions to be reached, most of which are presented in the Summary for Policymakers[1] (IPCC 2007d). Global temperatures are rising rapidly, by comparison with the natural fluctuations observed in available temperature records. The primary cause, almost certainly, is emissions of greenhouse gases, the most important of which is carbon dioxide, as a result of human activity. The consequences of a ‘business as usual’ (BAU) approach to climate change will be adverse and may be serious or even catastrophic.

Unfortunately, these general conclusions are at best modestly helpful in discussing optimal and feasible policy responses to climate change. To the extent that optimal policy responses are discussed at all, the usual approach is to consider solutions to complex dynamic stochastic models involving projected changes in output, greenhouse gas emissions and climate over future decades or centuries. When these models disagree, as they often do, it is difficult or impossible for anyone other than the modelers to determine the basis for the disagreement, let alone which model is correct.

Similar points have dogged the debate over feasible policy responses. One the one hand many participants in the debate assert, or implicitly assume, that ‘no regrets’ policies of various kinds will provide a sufficient response to the problems of climate change. On the other hand, there are claims that any effective response will entail the end of industrial civilization as we know it.

To complicate matters further, these claims commonly reflect strongly held ideological and social preferences, but the same claims are often made by people with diametrically opposed views. For example, some advocates of the view that climate stabilization would entail the end of industrial civilization see this as an argument for doing nothing in the hope that the problem will go away. Others see the end of industrial civilization as highly desirable and welcome the prospect that climate change will bring it about.

What is needed to resolve these difficulties is a simple and robust analytical framework, in which policy responses to climate change can be assessed on the basis of a small number of input parameters. To take this a step further, the input parameters themselves must be derived from a comprehensible process.

Given the complexity of the standard models of climate, economic activity and energy use, this task might seem hopeless. However, long experience of modeling suggests that in any large and complex model, a small number of equations, parameters and closure conditions determine, up to a good approximation, the results of crucial interest. This subset can be used to generate a small version of the full model, which can be used as a basis for analysis.

What is lost by doing this? The full model will give more disaggregated results on a larger number of variables, but for many policy purposes this is not necessary. The full model may also give an appearance of greater precision, by taking account of effects disregarded in the small model. However, this apparent precision is usually spurious. In most cases, uncertainty about input data swamps any approximation error associated with the simplified model. Finally, the modeling procedures used in constructing large models (such as general equilibrium models in economics) automatically impose consistency conditions which may be omitted in a simpler and less formal approach. On the other hand, in a simple model, such inconsistencies can easily be detected by a critical observer, which is commonly not the case for a larger model

In this paper, I will present a simple benefit-cost model to show that policy conclusions regarding the optimal response to climate change can be drawn from a model that is robust to a fairly wide range of possible inputs regarding both the benefits of climate stabilization and the cost of abatement and mitigation. The simple benefit-cost framework yields an optimal pair consisting of a carbon price (or marginal abatement cost) and an optimal target level for atmospheric concentrations of CO_2 and other greenhouse gases. The crucial observation is that given a quadratic loss function from uncontrolled climate change and a quadratic abatement cost curve, the optimal pair is robust to quite large changes in estimates of the most uncertain input parameter, namely, the cost of unmitigated climate change under BAU.

The model

The model is characterized by two equations, an abatement cost equation and a climate damage cost equation. In each case, the monetary cost is expressed as a quadratic function of the atmospheric concentration of CO_2 at which stabilization is achieved. Thus, we have

(1) $C_A(G) = k_A\,(G_{BAU} - G)^2 \quad G \leq G_{BAU}$

(2) $C_D(G) = k_D\,(G - G_0)^2 \quad G \geq G_0$

where

C_A = cost of abatement/mitigation

C_D = damage resulting from climate change

G = atmospheric concentration of CO_2 (in ppm)

G_{BAU} = atmospheric concentration under BAU (in ppm)

G_0 = atmospheric concentration consistent with minimal expected damage (in ppm)

k_A and k_D are parameters

For the mitigation cost equation (1), the quadratic functional form may best be understood in terms of a linear marginal cost of abatement. Taking derivatives

(3) $dC_A/dG = 2\,k_A\,(G_{BAU} - G)$

and the natural unit for the left-hand side is \$/tonne of carbon. From equation (3), the marginal cost of abatement at G_{BAU} is zero. It follows that G_{BAU} should be interpreted as the stable concentration that could be realized using only 'no regrets' measures, that is, measures for which the net benefits are positive even disregarding the effects on greenhouse gas emissions. We will set G_{BAU} at 650 ppm and G_0 = 350 ppm.[2] The minimum value is the most ambitious goal currently under debate, that of rapidly decarbonizing the economy and preventing serious damage. These estimates, and the associated emissions trajectories are discussed further in the Appendix.

It remains to determine k_A. For illustrative purposes, we assume that a carbon price of \$100/tonne, rising in real terms over time, would be required to achieve. This yields k_A = 1/6.

Turning to equation (2), it is easy to show that the projected damages from climate change must be represented by a strongly convex function of the ultimate change in temperature.[3] The increase of around 1 degree Celsius observed over the 20th century had few obvious impacts on human activity or natural ecosystems. Moreover, at least as regards human activity, it appears that any negative impacts were offset by the benefits of warming in some cold climates and the effects of CO_2 fertilization. An increase of 2 degrees warming, relative to the pre-industrial level is widely considered to be the maximum that would prevent serious damage. If the damage function were linear, this would suggest that the effects of more rapid warming would also be modest, at least by comparison with a growing global economy.

In reality, as the IPCC shows, warming of 4 degrees C would have a wide range of adverse effects on human activity, and would destroy large numbers of ecoysystems. There has been little modeling of the effects of 6 degrees of warming or more, but it seems clear that such warming would give rise to a mass extinction on a par with events such as the meteorite impact that ended the Mesozoic Era. The impacts on human activity would be unpredictable, but almost certainly catastrophic. It follows that the damage cost, expressed as a function of temperature change must be convex.

The relationship between temperature change and atmospheric concentrations of greenhouse gases is more complex. The climate forcing associated with greenhouse gases is proportional to the logarithm of concentrations, so that the fundamental relationship is concave. However, the final effect depends on a range of feedbacks which tend on balance to be positive and convex. So, most models yield a roughly linear relationship between concentration and temperature change. Hence, the the climate damage function (2), with atmospheric concentration as its argument inherits the convexity of the temperature-damage function.

Noting that, by definition $C_D(G_0) = 0$, we have

(4) $\mathrm{k_D} = C_D(G_{BAU})/(G_{BAU} - G)^2$

The most common way of expressing estimates for $C_D(G)$ is as an equivalent steady state reduction in income. We will initially consider the range of estimates presented by Stern (2007), from 5 to 20 per cent of income.

It remains to convert these estimates into the same terms as the LHS of (1) and (3), that is, dollars per tonne of CO_2. The first step is to convert the steady state reduction into a present value. We assume that income grows at 2 per cent a year, and use a real discount rate of 4 per cent. Current world income is around $US50*10^{12}$, so the present value of the income stream is $50*10^{12}/(0.04-0.02) = 2.5*10^{15=,}$ that is, 2.5 quadrillion dollars.

On the other side of the equation, 1 ppm of CO_2 by volume corresponds to approximately 7.5 Gigatonnes (Gt) of CO_2, where a Gigatonne is 10^9 tonnes. Since some emissions are absorbed by natural sink, we may use the slightly high and simpler conversion factor 1 ppm of $CO_2 = 10^{10}$ tonnes CO_2. Using the central Stern value of 10 per cent, and $(G_{BAU} - G_0)^2 \approx 10^6$, we obtain $\mathrm{k_D} = 2.5*0.1 = 0.25$

Now, differentiating (2) yields

(5) $\mathrm{d}C_D/\mathrm{dG} = 2\, k_D (G - G_0) = 0.5\, (G - G_0)$

Optimality requires that the optimal G^* satisfy $\mathrm{d}C_D/\mathrm{d}G^* + \mathrm{dC_A}/\mathrm{d}G^* = 0$, or

(6) $0.5\, (G^* - G_0) = 1/3\, (G_{BAU} - G^*)$

which yields the solution $G^*=470$, $dC_D/dG^* = 60$

In assessing the economic impacts of a carbon price at the levels derived from the model, the most appropriate starting point is to examine the revenue generated by such a price in relation to global income. At a starting price of \$60/tonne CO_2, with emissions of 30 Gt, CO_2-equivalents, a comprehensive carbon price would yield revenue of \$1.8 trillion, or around 3.5 per cent of global national income.

The optimal price increases in line with the real discount rate, assumed to be equal to the rate of income growth plus 2 percentage points. Thus, other things equal, revenue would grow faster than global income. However, the purpose of the carbon price is to reduce emissions. Stabilizing the global climate will require a reduction in emissions of approximately 50 per cent by 2050, which implies an annual reduction rate of around 2 per cent. Thus, the real increase in carbon prices would be approximately offset by the combined effects of declining emissions and growth in global income, so that the ratio of carbon revenue to global income would remain broadly constant.

The revenue derived from the carbon price is a transfer, not a social loss. Assuming, as in (3), that the abatement cost curve is linear, the social cost of abatement will be equal to slightly less than 50 per cent of revenue for the base solution where the price is \$60/tonne.

The estimated social cost is therefore around 2.0 per cent of income. The damage cost, relative to stabilization at 350 ppm is approximately 1.7 per cent of income. With the given illustrative values, BAU involves damage costs equal to 10 per cent of income and (by definition) mitigation costs of zero, so that the optimal policy yields a welfare gain equal to 6.3 per cent of income and a benefit-cost ratio of 2.7.

The logic of this analysis is robust to substantial changes in parameter values and functional form, provided the crucial convexity properties of the model are maintained. The marginal cost of abatement under BAU is zero by definition. By contrast, the marginal damage, while difficult to estimate precisely, is certainly substantial, given that the warming implied by BAU is well outside anything the human species has experienced. It follows that, with BAU as the initial position, there must exist substantial net gains from modest mitigation efforts (in fact, enough that, for large countries, some unilateral action would be beneficial even disregarding the effects on others). Since the optimal point is that where marginal benefits and costs are equal, the average benefit-cost ratio for an optimal mitigation program must be substantially greater than zero.

The effects of varying the key parameter values is shown in Table 1. For values of C_D(BAU), the damage cost under BAU, ranging from 5 to 20 per cent of income and full mitigation costs ranging from $50/tonne to $200/tonne, the show the optimal target (ppm), carbon price (S/ton) and welfare gain (per cent GDP). To guard against spurious precision, the optimal target is stated to the nearest 25 ppm, the price to the nearest $5 and the welfare gain to the nearest 0.5 percentage points.[4] Because both the abatement cost equation (1) and the damage equation (2) are strictly convex, the optimal solution is fairly robust to substantial changes in key input parameters.

TABLE 1 Near Here

The least favorable case for mitigation is that with C_D(BAU) set to 5 percent, and the full mitigation cost set to $150. In this case, the optimal target is 550 ppm, the carbon price is $50/tonne and the associated welfare gain is 2.0 per cent, reflecting a reduction in damage from 5 per cent of income to 3 per cent, with a mitigation cost equal to 1 per cent of income.

It is useful to compare this estimate with Stern (2007) who derived damage estimates ranging from 5 to 20 per cent of income, and argued in favor of a 550 ppm target. Stern did not present an explicit benefit-cost analysis. On the basis of the results shown in Table 1, the proposed target was at the upper bound of optimal outcomes, requiring both a high mitigation cost and a low damage cost. It is unsurprising, perhaps, that subsequent policy discussion has focused on lower targets, even if it has not produced an agreement on how to achieve those targets.

The most favorable case for mitigation is that with $C_D(G_{BAU})$ set to 20 percent, and the full mitigation cost set to \$50. In this case, the optimal target is 400 ppm, the carbon price is \$40/tonne and the associated welfare gain is 17.5 per cent, reflecting a reduction in damage from 20 per cent of income to 2.5 per cent, with a mitigation cost less than 0.25 per cent of income.

A notable feature of the two extreme cases is that they yield similar, and relatively low, estimates of the optimal carbon price. In the first case, the damages from climate change under BAU are relatively small, so that the marginal damage falls to \$50/tonne at the relatively high target of 550ppm. In the second case, the carbon price is bounded above by the parametric assumption that a price of \$50 is sufficient to achieve 350 ppm, at which point the marginal cost of emissions, given the assumed quadratic functional form, is zero.

Laving aside the extreme cases, the striking feature of Table 1 is the robustness of the key conclusions. For all but a few extreme assumptions, the optimal carbon price is between \$40 and \$75. Similarly, for a wide range of parameter values the optimal target is between 425 ppm and 475 ppm. In all simulations, the total cost of mitigation is below 5 per cent of income, and in most cases substantially below.

A closer look at the parameters

In the previous section, it was shown that for the suggested parameter values, a mitigation program with a target in the neighborhood of 450 ppm, as agreed in principle by most national governments, must be fairly close to the global optimum. In this section, the parameter values and the structure of the model will be considered in more detail. As in the previous section, the focus is on simple and transparent procedures for deriving robust bounds, rather on a quest for greater precision at the cost of complexity and (in)comprehensibility.

Abatement costs

As shown in (3), abatement cost is determined $2k_A\,(G_{BAU} - G_0)$, the price which generates sufficient abatement to stabilize global CO_2 concentrations at the 'safe' level G_0, here assumed to equal 350 ppm. Analysis of emissions trajectories (see Appendix) shows, that this requires essentially complete decarbonization of the economy by 2050, with gross human-generated emissions. Emissions from burning fossil fuels must be fully offset by activities such as forest expansion. Given zero gross emissions, natural sinks will gradually absorb CO_2 to permit the 350 ppm goal to be achieved.

The parameter value used in the illustrative case was $100. This is the price that would apply in 2010, rising at a real rate of 2 per cent per year thereafter. Hence, the price would reach $200/tonne a little before 2050. If, as required for the estimate to be valid, this price was effectively prohibitive, further increases after 2050 are essentially irrelevant.

The plausibility of the illustrative estimate may be tested in two ways, either looking forward from 2010 or considering the 2050 endpoint.

In considering the 2050 endpoint, the best way to consider the question is to examine whether it is likely to be feasible to replace all, or almost all, existing uses of carbon-based fuels with zero-emissions alternatives at a cost of $200/tonne. This question seems easy to answer in the affirmative as regards electricity generation, and relatively straightforward as regards transport.

With current technology, most of the main zero-emissions technologies had levelized costs close to, or below, $200/Mwh in 2010 (US EIA 2010, 2011). The exceptions, solar PV, solar thermal and offshore wind are all relatively new technologies, which may be expected to decline fairly rapidly. In particular, sharp declines in the cost of solar PV in recent years imply that the levelized cost is already well below $200/MWh. It is widely predicted that, in favorable locations solar PV will soon reach ‘grid parity’, the point at which unsubsidized PV is competitive with conventional sources (Lacey 2011)

Assuming a levelized cost of $100/MWh for coal and gas-fired generation, a carbon price of $200/tonne would increase the cost of coal-fired electricity to around $300/MWh and that of gas-fired electricity to around $200/Mwh, implying that these technologies would be more expensive than most current zero-emissions technologies. However, it is necessary to take technological change into account. Not only are the low-emissions technologies relatively new, therefore allowing more scope for innovation, but the induced innovation associated with a steadily increasing carbon price would favor these technologies. It follows that a price path rising from $100 to $200 would be more than sufficient to justify full decarbonization of the electricity sector.

In the transport sector, there are two alternatives to carbon-based fuels (oil and gas): biofuels and electric vehicles (noting that the electricity sector is assumed fully decarbonized). Both alternatives are currently feasible, but have a relatively small market share in the absence of subsidies or mandates. Estimation of abatement costs is difficult in view of the diversity of vehicles. However, it seems plausible that, given the incentives for innovation supplied by a high and rising carbon price, such alternatives would be able to displace carbon-based liquid fuels.

A significant difficulty in this context is that the principal carbon-based fuel to be displaced is oil, rather than coal or gas as in the case of electricity. Although, as current prices show, the marginal cost of extracting crude oil is around $100/barrel, large volumes of oil remain in the Arabian peninsula and elsewhere, for which the extraction cost is negligible. The supply from these sources is highly inelastic, implying that a decline in demand will be reflected in lower prices rather than lower quantities.

However, a growing proportion of crude oil can be expected to be used as a feedstock for petrochemicals rather than being burned for fuel. Petrochemicals currently account for around 10 per cent of total crude oil consumption.

It is not sufficient, however, that decarbonization should be feasible by 2050 given an end price of \$100/tonne. The starting price of \$100 must yield a sufficiently rapid decline in emissions over the intervening period. In this context, it is important to consider the full range of effects associated with equation (1), that is, substitution of alternatives for carbon, induced efficiency changes and demand response to an increase in the price of energy services.

The required rate of decline in emissions may be derived from equation (2). Since a proportional rate of decline can never reach zero, assume that the required decline by 2050 is 90 per cent, implying an annual rate of decline of 6 per cent. BAU allows for 1 per cent growth over the period 2010-2050, so the policy must induce an annual 7 per cent decline relative to BAU

Since the previous argument has shown the feasibility of the 2050 endpoint, the main concern is whether a price of \$100/tonne could deliver emissions reductions at an annual rate of 7 per cent relative to BAU.

The feasibility of this may be assessed using an accounting identity an accounting identity

(7) $C = P*(Y/P)*(S/Y)*(E/S)*(C/E)$

where

C is carbon dioxide emitted to produce energy

P is population

Y is aggregate income

S is energy services

E is energy consumption

In analyzing changes in emissions, it is useful to convert this into (natural) logarithmic terms

(8) $\Delta c = \Delta p + \Delta y + \Delta s + \Delta e + \Delta i$

Here

$\Delta c = \log(\Delta(C)/(C))$ is the rate of growth of (energy-related) emissions

$\Delta p = \log(\Delta(P)/(P))$ is the rate of growth of population

$\Delta y = \log(\Delta(Y/P)/(Y/P))$ is rate of growth of income per person

$\Delta s = \log(\Delta(S/Y)/(S/Y))$ is the proportional change in the share of energy services in total income

$\Delta e = \log(\Delta(E/S)/(E/S)$ is the proportional change in the ratio of energy use to energy services produced (the inverse of energy efficiency)

$\Delta i = \log(\Delta(C/P)/(C/P)$ is the proportional change in carbon intensity, that is, the ratio of CO_2 emissions to energy services produced

This identity includes no explicit role for prices. Consideration of income and price elasticities of demand, and of elasticities of substitution between energy and capital, and between energy from carbon and other sources, is crucial in understanding the likely impact of price based policies. For simplicity, consider the case where the price of carbon-based fuels is increased by 50 per cent (the effect of $100/ tonne carbon price would be higher than this for coal, but lower for oil). On the assumption that fuel costs constitute 50 per cent of the price of energy, this would entail a 25 per cent increase in energy costs, and assuming energy accounts for 40 per cent of the costs of energy-related services, a 10 per cent increase in the cost of those services.

Assuming that Δp and Δy are exogenous, the effect of a carbon price is given by the sum of changes in $\Delta s + \Delta e + \Delta i$, which as argued above, must sum to -0.07. A plausible combination would be annual Δi=- 0.04, Δe=-0.02, Δs=0.01. The implied elasticities over 10 years are below 1 in each case.

Damages of unmitigated climate change

The most difficult task in any economic analysis of climate change is the valuation of the damage likely to be incurred as a result of climate change, particularly under BAU, or other scenarios where the eventual concentration of CO_2 is well above the pre-industrial level. The range of uncertainty is huge

Further difficulties are created by questions about discounting, discussed by Nordhaus (2007), Quiggin (2008a,b), Stern (2007), and Weitzman (2007a), among others. The approach adopted here, using a discount rate two percentage points above the rate of growth of income is above that advocated by Quiggin and Stern, but below that advocated by Nordhaus and Weitzman, and is therefore relatively robust to differences in discounting frameworks. However, choices about discounting are always significant in evaluating benefits and costs decades into the future.

Most importantly, the two largest contributors to plausible estimates of expected damage are also the hardest to evaluate, though for rather different reasons. These are: the damage to natural ecosystems likely to occur with any significant increase in global temperatures over the next century or more; and the possibility of a catastrophic outcome, arising from some combination of high climate sensitivity and unexpectedly large feedbacks, yielding temperature increases of 5 degrees C or more.

There is little doubt that global climate change has already affected vulnerable ecosystems., These effects are virtually certain to become more severe, even at the relatively modest rates associated with aggressive mitigation programs. The consequences of warming of 3 degrees C or more, virtually inevitable under BAU are hard to comprehend, and equally hard to value.

Perhaps for this reason, cost estimates range from trivially low to extremely high. Nordhaus and Boyer (2000) are in the first category. Considering the possible extinction of between 15 and 40 per cent of all animal species, they impute a cost of \$2.5 billion per year for the United States, and \$1 billion for Europe. The latter sum also includes damage to cultural sites such as possible flooding in Venice. The implied cost of ecological disaster is of the order of 0.02 per cent of income or about 20 minutes of output per worker per year – a tiny fraction of the time that people spend watching wildlife documentaries, visiting national parks and so on.

On the other hand, advocates of zero economic growth have expressed a clear preference for a stable level of income as a way of minimizing ecological damage. Relative to projected growth of 2 per cent per year over the period to 2050, that implies that the loss of natural ecosystems would more than offset a doubling of income per person. Equivalently, avoiding this damage would be worth a 50 per cent reduction in income per person, relative to BAU, by 2050, and a much larger reduction by 2100.

With implied estimates ranging from 0.02 per cent of income to 50 per cent (a factor of 250), there is little likelihood of reaching agreement on a 'correct' answer. Many participants in the debate have therefore simply concluded that the costs of species loss under BAU are large enough to justify strong action to stabilize the climate, without any attempt at quantification.

The possibility of catastrophic climate change raises different difficulties. Estimation of the expected value low-probability events is always problematic. Subtle characteristics of the distribution of temperature changes, such as kurtosis ('fat tails') can result in the absence of any finite value for expected damage (Weitzman 2007b).

Returning to the consideration of equation (2), the proposed lower and upper bounds for $C_D(G)$ can be defended intuitively. As regards the lower bound, despite the difficulties of valuation, the risks of unmitigated climate change, including widespread species loss and the possibility of catastrophic climate change that an estimated cost below 5 per cent of income seems entirely implausible. While it is more difficult to assign an upper bound, it seems highly unlikely in practice that policymakers will take the kinds of measures that might be implied by estimated damages greater than 20 per cent of income.

Concluding comments

Climate change is easily the most complex environmental policy problem ever to have faced the global community. Arguably it is the most complex policy problem ever to have been systematically addressed by a formal process like that of the Intergovernmental Panel on Climate Change, drawing on the work large numbers of scientific research teams and public policy.

However, the sophistication of the analysis has itself proved problematic. An informed debate on policy responses requires an analysis that takes into account the relationship between human activity and climate change, the likely cost of climate change under various possible scenarios and the cost of mitigation.

Such questions can be addressed using integrated assessment models. However, while such models have made a useful contribution, their complexity means that participants in policy analysis must either invest a great deal of effort in understanding the workings of particular models, or else accept (or perhaps) reject model output on faith. Since there is substantial disagreement between the output of different models, this is a highly unsatisfactory situation.

In this paper, a simple two-equation benefit-cost model has been used to show that, under plausible assumptions about aggregate damage and cost functions, it is possible to derive estimates of optimal targets and carbon prices that are broadly consistent with those arising from international policy discussions such as those of the 2010 United Nations Climate Change Conference held in Cancún. Because of the convexity of aggregate damage and cost functions, these conclusions are robust to substantial variations in the crucial parameters of the model.

In summary, there seems little doubt that, given widespread implementation of a market mechanism yielding a carbon price in the range $US50-100, backed up by regulatory measures to promote energy efficiency, global CO_2 emissions could be greatly reduced at a modest economic cost. The result would be to stabilize atmospheric concentration at or near the level of 450 ppm which is, for median values of climate sensitivity, consistent with an ultimate warming of 2 degrees C. The net welfare gain from such an outcome, relative to BAU, would be substantial.

The main question facing the world is whether national governments can overcome both domestic opponents of action and the incentives to free riding on the efforts of others. If, as Stern has said, climate change represents the greatest market failure in history, then an inadequate policy response will represent one of the greatest of government failures.

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Appendix

This Appendix provides some estimates of feasible trajectories for CO_2 concentrations, and some discussion of their implications for global climate change. As with the main paper, the emphasis is simplicity and robustness, rather than precision.

Emissions and greenhouse gas concentrations

First, consider atmospheric concentrations of greenhouse gases, and the likely impacts on temperature. The current concentration of CO_2 in the atmosphere is around 390 parts per million (CO_2) by volume compared to a pre-industrial level of approximately 280 ppm. (IPCC WG1 2007).

As noted in the paper, the mass of the atmosphere is approximately $5*10^{15}$ tonnes. Because CO_2 is denser than air, 1 ppm of CO_2 by volume corresponds to approximately 7.5 Gigatonnes (Gt) of CO_2, where a Gigatonne is 10^9 tonnes. Human activity currently generates CO_2 emissions of around 30 GT a year of which about 40 per cent is absorbed by the ocean and other sinks, leaving a net increment of around 18 GT or approximately 2 ppm. So, if current emissions were sustained, and the effectiveness of sinks remained the same, atmospheric CO_2 concentrations would be around 560 ppm or twice the pre-industrial level by 2100.

However, emissions have been growing rapidly and, in the absence of mitigation it seems likely that they will continue to grow for some time. However, for a variety of reasons, it seems likely that emissions will decline after 2050 even under BAU.

* Although population projections are uncertain, most UN projections suggest that global population will either decline or grow very slowly after 2010

* Supplies of low-cost conventional oil are close to their peak values, and it seems likely that the use of oil for transport will be displaced by electricity in the long run

* Increases in energy efficiency available under 'no regrets' policies (included in the definition of BAU) are likely to be substantial.

For simplicity, assume that net emissions under BAU grow linearly until 2050, then decline linearly to zero over the period 2050 to 2100. A simple estimate of cumulative emissions and 2100 concentrations may then be obtained, given an estimate of the peak emissions level reached in 2050. Using the identity in equation (8), we will take baseline estimates of

$\Delta p = 0.01$

$\Delta y = 0.03$

$\Delta s = -0.01$

$\Delta e = -0.02$

$\Delta i = 0$

so that emissions over the period 2010-2050 are projected to grow at an annual rate of 1 per cent

A modification of this approach may be used to consider the emissions trajectories required for stabilization of CO_2 concentrations at lower levels and, in particular the levels derived as optimal using the model of Section 2. As noted by Garnaut (2011), it seems unlikely that feasible policies can achieve a trajectory of emissions which holds equivalent atmospheric concentrations of C). Hence, any feasible trajectory for stabilization involves 'overshoot'. That is, the maximum level of CO_2 equivalent concentrations will exceed 450 ppm, but emissions will be reduced to a level at which equivalent atmospheric concentrations decline to a level of 450 ppm (or perhaps lower). For an 'overshooting' trajectory to be consistent with stabilization of the climate, it is necessary that the period during which equivalent atmospheric concentrations exceed 450 ppm is short enough that temperatures do not fully adjust in line with climate sensitivity. Plausible trajectories involve a peak CO_2-e concentration of 500 ppm, which corresponds, in broad terms, to a peak CO_2 concentration of 450 ppm.

As noted above, CO_2 concentrations will begin to decline when emissions fall below the absorption capacity of sinks, around 12 GT a year. A trajectory in which this point is reached before CO_2-only concentrations exceed 450 ppm can be achieved if increases average 1 ppm per year over the next 60 years, falling to zero over this period, that is, a decline in gross emissions from 30 Gt to 12 Gt. A linear path implies that emissions should fall to around 18 GT by 2050, a global reduction of around 40 per cent.

Sensitivity and global temperatures

Discussions of climate science models commonly focus on a single key parameter, called 'climate sensitivity'. This is the long-run response of global average temperatures to a doubling of CO_2 levels relative to the pre-industrial levels.

The standard range of estimates for climate sensitivity reported in IPCC ARIII is

> likely to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded,

There is, however, substantial dispute over both the central estimate of climate sensitivity and the range of uncertainty. Moreover, this is not the only source of uncertainty. As well as uncertainty about future emissions, there is substantial uncertainty about possible feedbacks from climate to greenhouse gas emissions, such as the possible release of methane from melting Arctic tundras.

Although climate sensitivity is a useful summary statistic for the properties of climate models, it has important limitations in understanding the likely impacts of climate change. Climate sensitivity represents long-run response that will be realized over a period of some decades after CO_2 is emitted Typical estimates are 25 to 50 years.. Conversely, temperatures will take a long time (as much as 1000 years) to decline even after CO_2 levels are stabilized and begin to fall.

By contrast, many of the adverse impacts of climate change depend to a substantial extent on the rate at which climate changes. The faster is the rate of climate change, the greater the difficulty of adaptation both for human activity and for natural ecosystems. Furthermore, rapid climate change increases climatic uncertainty. In many agricultural contexts, climatic uncertainty is more costly than are non-stochastic differences between more or less favorable climatic conditions.

An important implication, which tends to be hidden by a focus on the eventual implications for global temperatures of a given emissions trajectory, is that the costs of climate change are not, or not exclusively, borne in the distant future. Rather, increased climatic uncertainty causes costs immediately, although it is difficult to disentangle these costs from those associated with natural climate variation.

Endnotes

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[1] It is important to note however, first that the Summary is a text negotiated between representatives of national governments, and second that the Summary is inevitably a simplification, and often an

oversimplification of a complex literature. Two main problems arise. First, the discussion tends to be overly conservative in drawing conclusions, particularly as regards the likely impact of climate change. On the other hand, there is a tendency to understate some of the uncertainties surrounding those points that are reported.

[2] In addition to CO_2, human-generated emissions of other greenhouse gases, including methane, nitrous oxides and chlorofluorocarbons must be taken into account. The non-CO_2 greenhouse gases are more potent than CO_2 in terms of their warming impact , measured by radiative forcing, but have a shorter residence time in the atmosphere.

The combined impacts of the greenhouse gases are commonly discussed in terms of a "CO_2 equivalent measure" of Global Warming Potential. In this paper, however, attention will be confined to CO_2 except where otherwise noted, and concentration measures will refer to ppm CO_2 only. This is consistent with the specification of the 350 ppm target by Hansen et al. (2008).

[3] More precisely, what matters is the rate of change of temperature over the period when it is likely to be most rapid, around the middle decades of this century. As is argued by Quiggin and Horowitz (2003), there is no reason to expect continuing net losses once economic activity and ecosystems have adapted to a new, warmer climate.

[4] In addition to the parameters explicitly included in the model, imprecision may be derive from uncertainty concerning the exact functional form of the damage and mitigation cost functions, problems of aggregation and discounting and so on. Thus, even the relatively limited precision of the estimates in the table overstates the accuracy of the estimates. On the other hand, as argued in the text, the robustness of the model means that the correct results cannot be substantially outside the range presented in the Table.

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