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The Economics of the Climate[†]

Geoffrey Heal*

I review the economic characteristics of the climate problem, focusing on the choice of discount rates in the presence of a stock externality, risk and uncertainty/ambiguity, and the role of integrated assessment models (IAMs) in analyzing policy choices. I suggest that IAMs can play a role in providing qualitative understanding of how complex systems behave, but are not accurate enough to provide quantitative insights. Arguments in favor of action on climate issues have to be based on aversion to risk and ambiguity and the need to avoid a small but positive risk of a disastrous outcome. (*JEL* D61, H43, Q48, Q54, Q58)

1. *Introduction*

Economists have been thinking about climate change since the 1960s, almost half a century now. Robert Ayres and Allen Kneese discuss the consumption of oxygen and its conversion to carbon dioxide (CO_2) in their 1969 paper in the *American Economic Review*, and Kneese went on to comment: "Should we need to control such things as the production of energy and CO_2 in the world, we will face an economic and political resource allocation problem of unprecedented difficulty and complexity" (Kneese 1971, quoted in Carson 2014), a prescient remark indeed. It was clear from the very start that this, as Kneese remarks, is a problem of unprecedented complexity, stretching to their limits the tools of economic analysis and in the process forcing us to refine them (see also Heal 1991). Initially, the literature on climate was limited, but during the last decade the number of contributions has grown exponentially. Two particularly interesting recent books are *Sustainability for a Warming Planet* by Humberto Llavador, John E. Roemer, and Joaquim Silvestre (hereafter, LRS) and *Climate Shock: The Economic Consequences of a Hotter Planet* by Gernot Wagner and Martin L. Weitzman (hereafter, WW).

There is one implication of the timescale of climate change that has been obvious from the word "go"—the discount rate matters. Climate change plays out over centuries, and choices over centuries are extraordinarily sensitive to discount rates. This has provoked intense debates about what is the "right" discount rate, and, more productively, about whether we are going about discounting the right way. Central to any such discussion is a distinction between the pure rate of time preference, the rate at which utility is discounted, and the consumption discount rate, the rate at

* Columbia University, Graduate School of Business and School of International and Public Affairs and NBER. My understanding of these issues has been greatly enhanced by discussions with Howard Kunreuther, Antony Millner, and Jisung Park.

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which the value of an increment of consumption falls over time. Under the right assumptions, these two are related by the famous Ramsey rule, as we will see below.

Additional elements of the debate are about whether we should use constant or declining discount rates, and about how we reconcile disagreements about discount rates within a community. Can we use political institutions to resolve discount-rate disagreements? Closely related is the choice of the elasticity of marginal utility, which like the discount rate has a profound impact on the relative merits of policy alternatives.

Think for a moment about the other elements of the problem. Clearly there is massive uncertainty. Although the underlying science is robust, some of the details are not, leading to many deep-seated uncertainties: we don't really know whether a business-as-usual scenario will lead to a global mean surface temperature (GMST) increase of 3°C or 6°C by the end of this century. And this 3°C discrepancy is not a detail: it could be the difference between a world where our present lifestyles can be continued and one where civilization as we know it has ended, although we don't know this for certain. Equally important, we don't know what the future will bring in terms of energy sources that don't produce greenhouse gases (GHGs), or technologies for removing GHGs from the atmosphere. To understand these issues, we need to peer at least half a century into the future, and we have only a rudimentary grasp of what kind of world we will live in then.

How to describe the uncertainties we face, how to model them, and what constitutes rational choice in the light of them, are therefore issues that are central to climate-policy analysis.

Substitution possibilities are at the center of understanding the long-run prospects in the face of climate change. How easy will it be to substitute clean for dirty energy? A subtler question concerns the substitution of produced goods and services for those derived from the natural world, something that will inevitably happen if we lose natural capital (forests, biodiversity) as a result of climate change. These issues are central to discussions of sustainability.

Many of these complexities are subsumed in the damage functions of integrated assessment models (IAMs), functions that relate temperature change to economic losses. While these functions are obviously central to the conclusions that emerge from IAMs, they are subject to all the uncertainties summarized above. They are supposed to map a change in temperature to a change in welfare, but most of the steps that link the former to the latter are uncertain, some highly so.

In the balance of this paper, I review each of these issues in turn, and consider how the contributions by LRS and WW address them.

2. *Discounting*

The standard philosophical framework for thinking about climate policies has been discounted utilitarianism, following the precedent of Ramsey (1928) and the intellectual traditions of John Stuart Mill and Jeremy Bentham. This is the default in almost every area of economics, though John Rawls has had his moment. Solow (1974) looked at intertemporal justice in a Rawlsian framework, as did Dasgupta and Heal (1979), and Heal (1998) compares Rawlsian and utilitarian formalizations of sustainability. The utilitarian framework has led to an intense focus on discount rates, with a secondary focus on the intertemporal elasticity of substitution. Both the pure rate of time preference and the elasticity go into the Ramsey rule for the social rate of discount

$$r = \delta + \eta g,$$

where r is the social rate of discount or the consumption discount rate, δ the pure rate of time preference, η the elasticity of marginal utility, and g the rate of growth of consumption. Almost all of the debate has been about the choice of δ. Most authors see this as an ethical parameter, reflecting judgments about the relative values of present and future people, in which case it is determined by introspection and discussion. To the extent that it is an ethical parameter, we cannot expect general agreement about its value—any more than we can expect general agreement about the appropriate distribution of income. Nordhaus (2007), however, has taken the view that δ can be determined by observing r as the return on capital, observing g, and guessing at η, perhaps on the basis of the progressivity of the tax system. But as the pure rate of time preference is an ethical parameter and rates of return are empirical facts, the illegitimacy of deducing an "ought" from an "is" seems to me definitive on this issue (as noted by David Hume and Immanuel Kant).

An irony that seems to have escaped most commentators is that while Nordhaus (2007), Stern (2006), and Weitzman (2007) all invoke the Ramsey equation in their choices of parameters, this equation does not in fact apply to the optimal climate-management problem. The reason is, of course, the external effect associated with the emission of GHGs—as Stern says, probably the greatest external effect in history. The classic Ramsey problem can be stated as

$$\text{Max} \int_0^\infty u(c_t) e^{-\delta t} dt, \frac{dk}{dt} = f(k_t) - c_t$$

where c_t is consumption at date t, and k_t the capital stock at that date, giving rise to the usual Ramsey equation as a first-order condition:

$$r = \frac{df}{dk} = \delta + \eta \frac{dc/dt}{c}.$$

If we modify the Ramsey problem to take account of climate change—as Nordhaus does in his Dynamic Integrated Climate and Economy (DICE) model—then the problem becomes

$$\text{Max} \int_0^\infty u(c_t)(1 - D(T_t)) e^{-\delta t} dt,$$

$$\frac{dk}{dt} = f(k_t) - c_t, \quad \frac{DT_t}{dt} = \alpha c_t$$

where T_t is the temperature at time t and $D(T_t)$ is a damage function denoting how much of output is lost because of climate damage. Here, the rate of change of temperature is assumed to depend on the level of consumption, a proxy for industrial activity. The equivalent to the Ramsey equation in this model is

$$\left\{ \eta \frac{\dot{c}}{c} + \delta \right\} \frac{[\lambda - \alpha\mu]}{\lambda}$$
$$+ \frac{\alpha}{\lambda} \left\{ \left\{ \delta\mu + u \frac{dD}{dT} \right\} - u' \frac{dD}{dT} c \right\}$$
$$= \frac{df}{dk} = r$$

where λ is the Lagrange multiplier or shadow price associated with capital stock and μ that associated with the temperature, so, as one might expect without going through the math, the relationship between the social discount rate and the pure rate of time preference depends on the nature and extent of the externality inflicted by climate change. This equation reduces to the usual Ramsey equation if there are no damages from temperature change (α=0). To assert that the normal Ramsey equation holds is to assert that climate change doesn't matter.

Weitzman (2001), Gollier and Weitzman (2010), Gollier (2012), and others have recently drawn attention to the possibility that the consumption discount rate r may decline over time, and indeed both the governments of the United Kingdom and France have now institutionalized declining discount rates for cost–benefit analysis (for a review see Arrow et al. 2014). The Ramsey equation shows that this is clearly possible: indeed, if we apply it to Ramsey's own results then, along an optimal path in his model, consumption asymptotes to a constant value and g goes to zero, so r declines to the pure rate of time preference, meaning that declining consumption discount rates have always been implied by the neoclassical optimal growth model. A more disruptive suggestion has also emerged recently: that the pure rate of time preference δ should also be time varying and decline over time. This idea emerges as a response to the observation that different people have different pure rates of time preference, and that there is therefore a need for some institution to reconcile these differences and find a rate that is in some way acceptable to all. Gollier and Zeckhauser (2005) suggest that this should be done by finding an efficient discount rate, one that maximizes a weighted sum of all individuals' utility integrals: this would provide a Pareto efficient time path. They show that in a very simple economy with a constant exogenous flow of aggregate income, this involves a nonconstant pure rate of time preference that declines over time. Heal and Millner (2013) extend this to a more general model, and go on (in Millner and Heal 2014) to compare economic and political mechanisms for reconciling divergent opinions about the correct value for the pure rate of time preference.

LRS make very interesting and novel comments about discounting and more generally about the philosophical framework within which most economic analysis of climate change is conducted. *Sustainability For A Warming Planet* combines an innovative integrated assessment model with a thought-provoking discussion and critique of many of the methodological issues that underpin the use of such models.

LRS place their IAM not within the normal utilitarian framework, but within what they term a *sustainabilitarian* framework, which deals in levels or rates of growth of welfare that can be maintained indefinitely. They take the Solow–Rawls idea that future generations have a right to the same living standard as the present and supplement it with its reverse, namely that the present has a right to the same living standard as the future. Additionally, they invoke the brute luck/option luck distinction, brute luck being the outcome of lotteries against which no one can insure and option luck referring to gambles that one can choose to take or not. So being born talented or with a genetic disposition to cancer are examples of (good and bad) brute luck. Making a successful investment is good option luck. Arguing with the luck egalitarians that benefiting from brute luck is illegitimate supports LRS's basic assumption that no one has a right to a higher living standard because of the date of their birth (brute luck), and hence one should seek the maximum sustainable living standard. Their criterion is actually to maximize the welfare of the first generation, subject to ensuring that welfare grows at no less than a specified rate a forever. If that rate is zero, they have the Rawlsian case. However, they argue that humans have a natural desire to see the species progress, which implies that early generations are willing to accept a positive a and its concomitant lower initial consumption levels in exchange for progress in the long run. They then refine this argument, and pin down the value of a by assuming that each generation has a recursive utility $V_t = (u_t)^b (V_{t+1})^{(1-b)}$. In this case, they show, maximizing the utility V_1 of the first generation involves maximizing the instantaneous utility u_1 of that generation subject to a growth rate of future instantaneous utility that is a function of the parameter b. There is no formal axiomatic framework for this criterion, but, as noted above, it is justified intuitively by reference to Rawls (1971), Dworkin (1981), and luck-egalitarianism (Roemer 2009), which make a plausible case.

Three more features of the LRS model mark it out very sharply from the standard IAMs. One is the lack of a conventional damage function: they have picked a framework within which there is no need to model explicitly the damages resulting from climate change. As the damage function is the weakest part of any IAM, this is an interesting gambit. How do they do this? By taking the Intergovernmental Panel on Climate Change's (IPCC) Representative Concentration Pathway (RCP) 2.6 as a constraint. RCP 2.6 is the low-emissions pathway that ensures that the change in global mean surface temperature (GMST) does not exceed 2°C, a number widely accepted as the international goal and often interpreted as the maximum "safe" increase. So their model maximizes the criterion function of the previous paragraph subject to GHG emissions not exceeding those on RCP 2.6. The damage function is replaced by a constraint that no major damage be done. The immediate question is then, are there feasible solutions, and if so, how appealing are they?

The idea of not using a damage function will come as a shock to most economists familiar with the existing literature, but it has a lot to recommend it. The damage function is probably the weakest part of any IAM (see Pindyck 2013), so the LRS approach is dropping the weakest link in the analytical chain. But what is it replaced by? Using RCP 2.6 as a constraint is in effect adopting the scientific community's view of the damage function, which is that climate change becomes "dangerous" above 2°C. It is equivalent to introducing a damage function with a trade-off between economic activity and climate that changes very sharply at 2°C, and so represents an implicit damage function that is far more severe than any in the literature to date. Nordhaus's DICE model suggests that 2°C leads to a loss of GDP on the order of 1 percent, which is negligible. Haneman (2010) and Weitzman (2010) suggest that Nordhaus's damage function is far too optimistic, but the changes they make affect largely the damages at temperature increases in the range of 4°C+: they all agree that the damages from a 2°C temperature increase are in the low-single figures in terms of percent of GDP, less than the loss of GDP from the recession of 2007–09. So even the most severe damage functions in the current IAM literature are far less pessimistic than LRS implicitly are in their interpretation of the temperature–damage relationship—which is not to say that LRS are wrong: we return to this below.

Another damage-function replacement in LRS is the presence of GHG concentration as arguments of the utility and production functions: in the utility function, welfare falls if GHG concentrations exceed a "catastrophic" level, corresponding roughly to a temperature increase of 6–8°C. They chose the exponent of this to match the *Stern Review*'s estimate that a 5°C increase over preindustrial levels would lead to nonmarket damages equivalent to a loss of 6 percent of world GDP. Greenhouse gas concentrations in the utility function are a proxy for the state of the global environment in general, such as loss of species, disturbance to traditional weather patterns, and other losses of environmental amenities. It is to the *Stern Review*'s credit, and that of LRS, that these factors are included, but I suspect that the weighting given them is low relative to their real importance. Some measure of environmental capital has featured as a source of well-being in theoretical models of conservation since Krautkraemer (1985), and has been extensively used by Chichilnisky, Heal, and Beltratti (1995), Heal (1998), and Sterner and Persson (2008), among others.

Thinking about the damages from climate change highlights a disagreement that has worried me for some time now. Scientists working on climate change take it as almost axiomatic that an increase in GMST of 2–3°C would be devastating and would inflict massive costs on our societies. This belief seems to be based in part on studies of the paleoclimate record, and in part on intuition about the interactions of the complex systems that constitute the environment we live in. Take the paleoclimate record: this indicates that when CO_2 levels were in the 400–450ppm range—where we are today—sea level was fourteen meters higher than today (Hansen et al. 2016), implying that this is possibly the equilibrium sea level associated with such CO_2 concentrations. It is widely asserted that it will take centuries to reach this equilibrium, so even if these statements are true, our generation will not be affected. But if we really are committed irrevocably to such a destructive rise in sea level in the long term, should we ignore it? Recently, Hansen et al. (2016) have argued that the timescale for sea level to rise significantly is far shorter than previously thought, implying a rise of several meters this century.

Yet nothing in the emerging econometric studies of the impact of climate on economic activity confirms these dramatic concerns (Houser et al. 2015). A one-degree increase in temperature might lead to a drop in output of 2–4 percent in general, and perhaps more in the agricultural field: indeed a 5°C increase could lead to a 50 percent drop in agricultural output, according to some studies (Schlenker and Roberts 2009). Yet all of these results taken together do not suggest that there is a massive increase in damages at 2°C, or a huge risk to exceeding this number by a modest amount. It seems that in this debate, one side is wrong, perhaps both. I am certainly willing to bet on economists underestimating the costs of climate change, because it is only in the last two decades that we have started to look for them, and only in the last few years that this has become a mainstream activity. In the last few years, our estimates of the damages have gone only one way—upwards. There are certainly still many aspects of the damages from climate change that we have not yet quantified—for example, those linked to the loss of biodiversity and associated ecosystem services, or those linked to the acidification of the oceans, so we are clearly underestimating the damages. But it is also possible that scientists underestimate the resilience of socioeconomic systems. Unfortunately this disagreement is not likely to be resolved in the near future, simply because we don't have the evidence needed for a clear resolution. During the historical record, climate has varied far too little for us to be able to estimate its economic consequences, let alone predict the consequences of a change way outside anything that has ever been seen by humans. The bottom line, then, is that LRS are betting that the scientific intuition about 2°C being the safe limit for climate change is correct: I am not sure they are right, but neither am I sure they are wrong. It does seem worth investigating the implications.

Before understanding the consequences of replacing a damage function by a constraint given by RCP 2.6, we need to understand another distinctive feature of the LRS model: the presence of an educational sector that drives increases in productivity. Productivity growth is endogenized along the lines of endogenous growth theory, an intellectually appealing but empirically challenging strategy.

The model addresses intratemporal, as well as intertemporal, equity and does so by modeling two sectors, developed and developing countries, the former parameterized by numbers from the United States and the latter by Chinese numbers. The authors take as a constraint that whatever policies are implemented to avoid dangerous climate change must be politically acceptable to the developing world, by which they mean that the date at which China catches up with the United States in per capita terms must not be delayed by climate policies. This date they assume to be 2085.

So we now have the entire model: maximize the utility of the first generation given recursive preferences, subject to not exceeding emissions on RCP 2.6 and not delaying the convergence of developing and developed countries, in a model with endogenous productivity growth. It's very different from what most readers of this journal are used to, but I find it appealing and clearly well worth exploring.

Returning to a question left on one side earlier, there are feasible solutions: this may have something to do with the endogeneity of productivity growth. It is possible for rich countries to grow at 1 percent annually and poor countries at 2 percent annually until they converge in 2075, and then for both to grow at 1 percent annually, and still respect the constraint of RCP 2.6. So we can have growth, convergence, and no damage from climate change, but the growth has to be slower than we are used to, on balance an optimistic outcome.

I am never completely certain how to take the numbers coming from an IAM. Certainly they are not serious forecasts—none of the models are nearly good enough for that. In this respect economists' models are very different from the global circulation models of climate science. I think of IAMs as tools for exploring qualitative relationships in models that are too complex for analytical solutions, and for, perhaps, getting some sense of the orders of magnitude of some important effects. Viewed this way, the LRS model seems as worthy of consideration as any of its competitors, and the absence of a damage function, together with its north–south dimension and endogenous growth of productivity, mean that it brings novel and valuable perspectives to the party.

3. *Sustainability and Substitution*

Climate change and sustainability are not the same topic, but they are related, and LRS invoke both in their title *Sustainability for a Warming Planet*. Sustainability is best understood as referring to forms of economic and social activity and organization that can be continued for long periods without significant harm. The use of fossil fuels clearly does not meet this definition, and the drivers of climate change are prime examples of unsustainable behavior. But they are clearly not the only ones: soil degradation, deforestation, and loss of biodiversity are other aspects of our current behavior that are not sustainable.

One way of defining sustainability is in terms of capital stocks: an economy is sustainable if the total value of all its capital stocks, evaluated at shadow prices, is constant or increasing. Intuitively this is related to John Richard Hicks's definition of income as the maximum you can spend this month, consistent with spending the same in all subsequent months. This definition implies that income is return on capital, and income in this sense is sustainable if capital is nondecreasing. Capital here has to be interpreted very broadly, to include natural, human, and intellectual capital as well as conventional capital goods. Heal and Kriström (2008) have a formal statement of these results and a survey of related work, and Heal (2012) has an exposition. These ideas tie into the World Bank's work on adjusted net savings (ANS) as a measure of sustainability (World Bank 2011). ANS is precisely the change in the value of capital stocks broadly defined that we refer to above as the criterion for determining whether an economy is sustainable: it's the sum of the changes in all kinds of capital stock valued by their shadow prices.

There are actually two concepts of sustainability to be found in the literature, weak and strong. Weak sustainability is what we just discussed: a nondecreasing trajectory for the value of total capital. Strong sustainability is a nondecreasing trajectory for natural capital, just a part of the total (see Neumayer 2013). This is a much more demanding criterion: natural capital is unambiguously decreasing and it is clear that the world is not strongly sustainable. It is, however, possible that the decreases in natural capital are being offset by increases in physical, intellectual and human capital, so that the world is weakly sustainable. Indeed several recent publications suggest that this is the case for the United States and China, although not for sub-Saharan Africa or the Middle East (Arrow et al. 2004, 2010). A world that is weakly but not strongly sustainable is only possible if the elasticities of substitution between natural and other forms of capital in production and consumption are high enough, and this is a topic on which we know little.

This leads to a discussion of substitution possibilities between "natural" and "human-made" capital. It is natural to think that these two are arguments of both the production and the utility functions, so the sustainability of growth will depend on the possibility of substituting between them. Natural capital is limited in amount, and its destruction, which is happening all the time, is largely irreversible. So to the extent that it is important in either welfare or production, this will place limits on the sustainability of human well-being. Substitution possibilities between natural and other forms of capital have not been widely discussed: Dasgupta and Heal (1979) discuss whether or not natural resources are essential, in the sense that without them it is possible to guarantee a continuing reasonable standard of living, linking this to the substitution elasticity between natural and other forms of capital. Heal (2009) begins this discussion in the context of preferences, suggesting that a certain minimum level of natural capital might be needed to maintain human well-being, which would imply that substitution possibilities between natural and other forms of capital are ultimately limited. Sterner and Persson (2008) investigate this issue in Nordhaus's DICE model, making utility a function of conventional consumption and a flow of services from natural capital. On the basis of a rough calibration of the model, they suggest that this greatly increases the optimal abatement of greenhouse gases.

4. *Uncertainty*

Uncertainty is fundamental to the climate problem: as Heal and Millner (2014b) point out, we face both scientific and socioeconomic uncertainty, that is, uncertainty about the underlying science of climate change and also uncertainty about the economic and social impacts of an altered climate.

It is standard to decompose scientific uncertainty into model uncertainty, internal variation, and emissions-scenario uncertainty. Model uncertainty refers to the need to choose amongst alternative mathematical representations of the physical and chemical processes governing the climate without clear knowledge of which is best. Climate models are complex and highly nonlinear, and so prone to chaotic behavior, meaning that they display sensitive dependence on initial conditions. So small discrepancies in the estimation of initial conditions can lead to large difference in forecasts, and as initial conditions are never known with certainty (for example, our network of climate sensors is quite sparse) this is another source of uncertainty in estimates of climate change, called internal variation. All climate forecasts are driven by emissions scenarios, which require forecasting future economic activity and its emissions intensity, both hard to project with any great confidence. Over time horizons in excess of fifty years, emissions uncertainty is generally the greatest source of uncertainty (see Hawkins and Sutton 2009).

Socioeconomic uncertainty is divided into positive (or model) uncertainty and normative uncertainty, the former arising from our not knowing how to model accurately the effect of climate on economic and social activity and the latter arising from our uncertainty about the choice of discount rates and elasticities.

Furthermore, the uncertainty we face in all categories is particularly challenging because we don't have anything like objective-probability distributions to describe it. In fact, it's far from certain that we have anything resembling subjective-probability distributions: we are dealing mainly with qualitative uncertainty, ambiguity, rather than risk in the traditional Knightian risk/uncertainty dichotomy. The IPCC in its assessments of the science of climate change goes some way to acknowledging this, ranking the degrees of uncertainty associated with conclusions.

This argues powerfully for the inclusion of uncertainty as a central aspect of climate-policy analysis, and not just a routine treatment of uncertainty assuming a full set of probabilities, but a more sophisticated treatment allowing for ambiguity. A literature on this is beginning to emerge—see Millner, Dietz, and Heal (2013) and Lemoine and Traeger (2012), which show that aversion to risk and ambiguity both play a major role in policy analysis, and that ambiguity aversion is not just an addition to risk aversion, but can drive policy choices in different directions.

Climate Shock: The Economic Consequences of a Hotter Planet by Gernot Wagner and Martin Weitzman comes into its own here, emphasizing the centrality of uncertainty and the role of climate policy as planetary risk management. The authors are very good at arguing that uncertainty is not an excuse for doing nothing or for a wait-and-see policy. But given Weitzman's contributions to the field, this is hardly surprising. *Climate Shock* is a very different book from *Sustainability for a Warming Planet*, intended not as academic research but as a contribution to the public education and debate about the need for action on climate change. So the relevant question is not whether it is original but rather whether it represents economic understanding appropriately and communicates it successfully.

Posing climate policy as an exercise in risk management is appealing. As one representative passage in *Climate Shock* argues,

> We don't know the full implications of an eventual 6°C (11°F) temperature change. We can't know. It's a blind planetary gamble. Devastating home fires, car crashes, and other personal catastrophes are almost always much less likely than 10 percent. And still, people take out insurance to cover against these remote possibilities, or are even required to do so by laws that hope to avoid pushing these costs onto society. Risks like this on a planetary scale should not—must not—be pushed onto society.

The insurance analogy is an appealing metaphor, but when you think about the details it's not quite right. When we insure, we sell a risk that we bear to someone else who was not bearing it and who now assumes it. They then effectively annihilate it through risk pooling and the law of large numbers. When the planet is at risk we can't do this: there isn't anyone else who is not exposed to whom we can sell our risk. Insurance isn't quite the right metaphor: risk management in some generalized sense, yes, but not traditional insurance. In fact, insurers are very disturbed by the prospect of climate change, as it threatens them with correlated risks (not the usual IID risks of the law of large numbers) and risks whose probabilities are not known, in contrast to conventional property and casualty risks whose characteristics are well-documented and the domain of traditional insurance.

WW argue that focusing on the most likely outcomes under climate change lulls us into a false sense of security, because (putting it more technically than they do) there is plenty of probability mass remaining in the right tails of the relevant distributions. The "most likely" range for the equilibrium climate sensitivity (ECS, which tells us the long-run equilibrium increase in GMST resulting from a doubling of CO_2 concentration) is in the region of 1.5 to 4°C, but some highly-reputed climate models give a chance of at least 15 percent that it is no less than 6°C. As we are likely to double CO_2 concentrations relative to preindustrial levels within forty years, and 6°C is a catastrophic increase in temperature, this is a highly disturbing situation and talking only about the 1.5–4°C range misses the worrying feature. This is a very valid point indeed, and one that I and others (Kunreuther et al. 2013) have made in criticism of the IPCC, which focuses almost entirely on the most likely outcomes in its summaries for policy makers and neglects tails.

This discussion of the tails of the risk distribution raises a deeper question. When WW talk of "the distribution," which distribution are they talking about? Figure 1 shows the question: twenty different estimates of the density function of the ECS, coming from Monte Carlo simulations of twenty major climate models. These are not independent estimates of an underlying true distribution—firstly because there is no underlying distribution, as the ECS is a number, and secondly because they are all calibrated on the same data sets and represent the same laws of physics. So we can't combine them into one. These PDFs are all heavily dependent on expert judgments, as the Monte Carlo simulations are based on probability distributions over parameter values judged appropriate by the modelers. A similar picture could be drawn for most aspects of climate uncertainty: there is rarely a single distribution describing the possible outcomes. While *Climate Shock* is largely about what we don't (yet) know or perhaps can't know, WW don't talk about the distribution question directly. In fact, they discuss their choice of a distribution in one of the many substantive end notes. Presenting a picture akin to figure 1 below would also have helped their cause, because it reinforces their main point that we are facing the possibility of very bad outcomes and can't assert that they are "very unlikely." Rational conduct under these circumstances clearly requires active management of the risks. A decision criterion such as the Gilboa–Schmeidler maxmin expected utility criterion, which tells us to judge policies by the probability distribution that makes them look least favorable, leads to conclusions very consistent with the points that WW are making.

LRS also address uncertainty, devoting the final chapter of *Sustainability for a Warming Planet* to a stochastic version of their model. The uncertainty is not about the magnitude of climate change, but about timing. There are two cases. In the first, they assume that climate change may lead to the destruction of the human population at an uncertain date: there is a hazard rate that rises with the concentration of CO_2 in the atmosphere. In this case, the authors maximize the expectation of what is essentially a modified Rawlsian objective. For each realization of the stochastic process, the utility is T times the minimum of the generational utilities u_t, where T is the number of years until the destruction of the human population. So if this is T', utility is $T' \min_t\{u_t\}$, and the maximand is the expectation of this. Note that if the individual values of u_t are random, then the minimum of these is described by an extreme value distribution. LRS are unable to perform a full optimization for this case and instead run simulations of the model to find a "good" outcome. Although they do not have a fully optimal solution, their simulations lead them

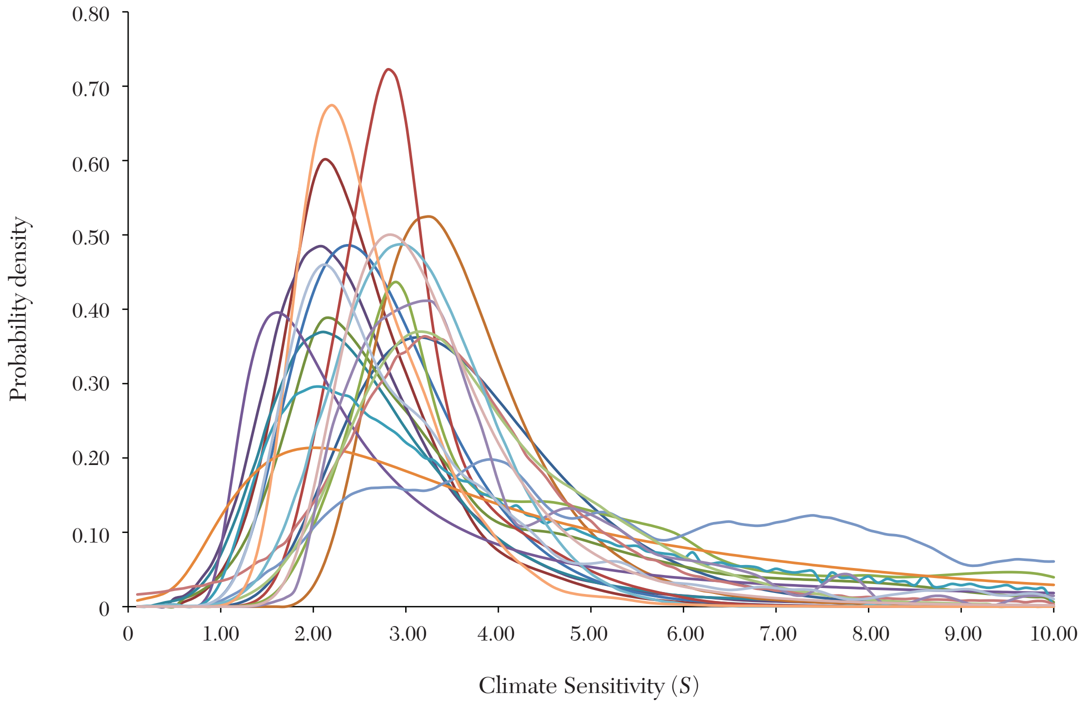

Figure 1. Estimates of the Probability Distribution for Climate Sensitivity

Source: Millner, Dietz, and Heal (2013)

to suggest that the possibility of extinction with a rather low hazard rate, taken with the objective function described above, leads to very cautious behavior with CO_2 concentrations between 350 and 400ppm—below where we are today. Their hazard function is parameterized so that the probability of extinction at 700ppm is twice that of the preindustrial era, which seems a very low risk. It is surprising that such a low hazard rate leads to such cautious behavior: this is presumably related to the choice of objective, and to the fact that CO_2 concentrations on RCP 2.6 are programmed into the model as a constraint.

LRS also consider a second case in which the catastrophe caused by climate change does not eliminate the human species but renders our capital equipment far less productive forever. (Heal 1984 considered exactly this case, in the context of a Ramsey–Solow model.) They are not able to produce numerical results for this case, but provide an analytical framework for thinking about the issues raised.

Overall, the treatment of risk in the LRS model is limited, as they themselves admit. The treatment of uncertainty in climate models is a growing field and its incorporation, as LRS suggest, can alter the conclusions in important ways, adding strength to the case for action—which is one of the main points of the WW book. Cai et al. (2013), Lemoine and Traeger (2012), and Millner, Dietz, and

Heal (2013) all show that uncertainty can increase the optimal level of GHG abatement. Cai et al. and Lemoine and Traeger (2012) work in models with tipping points at which a continuous change in GHG concentration can lead to a discontinuous response in damages, aiming to model the crossing of thresholds that might, for example, lead to a change in the patterns of thermohaline circulation or to the release of massive amounts of methane from permafrosted regions. Lenton et al. (2008) provide a survey of possible climate tipping points. Millner, Dietz, and Heal (2013) work with more conventional damage functions than Cai et al. and Lemoine and Traeger (2012), and study the optimal abatement policies in the presence of ambiguity rather than risk. Lemoine and Traeger (2012) combine the two.

5. *Geoengineering*

WW devote a lot of energy to discussing geoengineering, arguing that it is not a real substitute for effective action on climate change. The form of geoengineering that they focus on is the widely discussed idea of releasing sulfates high in the atmosphere: these would form small particles that reflect sunlight and reduce the radiative forcing of the earth. This is a relatively inexpensive and technologically simple way of reducing the earth's heat load (see Barrett 2008). It doesn't remove CO_2 from the atmosphere but offsets some of its effects, in particular its effect on radiative forcing. It does not reduce the concentration of CO_2 in the oceans and the extent of ocean acidification, nor the direct effects of CO_2 in the atmosphere, such as CO_2 fertilization of plants.

The striking feature of this form of geoengineering is that almost any country could do it, at least crudely—indeed a billionaire with a fleet of aircraft at his disposal could also change the earth's climate this way. That's not a particularly likely scenario, but it is a possibility. Note that it's not something you do only once: the sulfate particles fall to earth within a year or so, meaning that they have to be continuously resupplied. The impact of a major volcanic eruption is a good model: these release millions of tons of sulfates into the air, and big explosions (Tambora, Krakatoa, and Pinaturbo) have always cooled the global climate for one or two years following, with the effects dying away as particulates return to earth. So in the event that climate change has a harmful impact on one country or region of the world (for example, it stops the Indian monsoons, wreaking massive damage on that country's agriculture), that country or region could implement geoengineering unilaterally. A problem here is that while the release of reflective particles into the stratosphere might restore GMST to its previous levels, it might not restore the actual weather patterns associated with those earlier temperatures, and could in fact lead to changes in weather patterns that harm some regions—possibly including the originating region. So the ease with which geoengineering could be implemented by a "rogue" state worries WW. However, it could still be a valid part of a last-resort response to extreme climate change, though ideally only as part of a global agreement.

There are other forms of geoengineering that are perhaps more appealing, for example, direct removal of CO_2 from the atmosphere and underground storage in empty gas or oil wells or mineralization in porous rocks. Several start-up companies are working on this,[1] and it does fully reverse the emission of CO_2 from burning fossil fuels, removing CO_2 from the air and the oceans and undoing all of its impacts, from radiative forcing to ocean acidification. It is however currently far more expensive than injecting particles

[1] Carbon Engineering and Global Thermostat.

into the stratosphere, seemingly in the region of \$150–200 per ton of CO_2 removed.

This estimate of the cost of removing CO_2 is way above common estimates of the social cost of CO_2 emissions, with the US administration's current best estimate being somewhere around \$40 per ton (and possibly as high as \$100) depending on the discount rate and some other assumptions.[2] As long as the cost of removing CO_2 exceeds the social cost of carbon, there is no justification for implementation as a public policy. However, the cost of removal is expected to fall over the next decade, and the current estimates of the SCC are probably serious underestimates. They use discount rates that many commentators consider to be high (2.5–3 percent, as opposed to <1 percent in the *Stern Review*), they use a constant rather than a declining discount rate (which would boost the cost significantly, see Heal and Millner 2014a), they omit any consideration of uncertainty, which, as we have seen, will boost the SCC, and they fail to quantify many of the damages due to climate change (biodiversity loss, for example). LRS provide an estimate of the SCC based on their model, which, as we have noted, has in effect a far more severe damage function than the normal run of IAMs—their estimate is \$633 per ton of CO_2. So it is possible that it is already, or could soon be, socially profitable to use existing technologies to remove CO_2 from the atmosphere. We might pay for this by a tax on GHG emissions.

6. *What's Missing*

There are two topics that have featured largely in the economics literature on climate, but are omitted from both books under review. The international negotiation process that has occupied so many highly qualified people for so much time every year since the formation of the United Nations Framework Convention on Climate Change (UNFCCC) has rightly been the object of extensive analysis and a substantive literature, and our lack of a good grasp of the damage function relating temperature change to economic consequences has given rise to a burgeoning econometric literature on the effect of temperature and other aspects of weather on economic performance. *Sustainability for a Warming Planet* does not need to address these literatures, as it specifically eschews the use of a damage function of the conventional type and does not venture directly into policy prescriptions. *Climate Shock*, on the other hand, is a policy-oriented work, and some comments on how we get from concern, the need for which it clearly documents, to action, could be a valuable addition. There is a thoughtful chapter on *What You Can Do*, focusing on how an individual can contribute, avoiding and going beyond the usual "top-ten" lists of biking, recycling, and other environmental pet peeves, but it doesn't ask how we can transform the UNFCCC talking shop into an action program. And although *Climate Shock* emphasizes the seriousness of the consequences of climate change, it doesn't spell out in any detail what these are.

What might have been included? Certainly some discussion of the current international policy framework and its strengths and—more particularly—weaknesses. Barrett (2005) is a good place to start, though the field has grown since then, with ideas about climate clubs (Nordhaus 2015), tipping climate negotiations (Heal and Kunreuther 2012), and bottom-up climate policies (Stewart, Oppenheimer, and Rudyk forthcoming).[3] All these new contributions suggest that perhaps the entire membership of

[2] See: US Interagency Working Group on Social Cost of Carbon (2010), and the July 2015 update: US Interagency Working Group on Social Cost of Carbon (2015).

[3] A very thorough review is in Aldy and Stavins (2010).

the United Nations is not the best group for reaching an agreement on reducing GHG emissions, and that we should seek to work, at least initially, with smaller groups whose members have leverage over nonmembers. The recent bilateral negotiations between the United States and China seem to exemplify what these recent papers have in mind. In addition, they suggest that rather than focusing exclusively on emissions targets and timetables, negotiations also focus on the deployment of renewable energy and the introduction of policy frameworks that encourage this.

With respect to damage functions, there is an emerging literature but we are far from having a comprehensive understanding of how weather and climate affect economic outcomes. Best understood is the impact on agriculture, where a substantial literature (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2005; Schlenker and Roberts 2009; Dêschenes and Greenstone 2007) suggests that a few days of exposure to temperatures above about 31°C are very harmful to the yields of several important food crops. There is also a growing awareness of the consequences of higher temperatures for overall productivity, suggesting that, at least in hot countries, this falls sharply in hot weather (Dell, Jones, and Olken 2012; Heal and Park 2013; Heal and Park 2015; Cachon, Gallino, and Olivares 2012). We also know that sea-level rise will be costly (Yohe, Neumann, and Ameden 1995), but don't know how temperature changes translate into the melting of ice sheets and a rise in sea level. This diverse literature is pulled together well by Houser et al. (2015) in the case of the United States, with a comprehensive integration of how all the known microeconomic impacts of temperature will play out in the case of the United States, and a very appropriate and humbling emphasis on the size of the error bars in any forecasts. It is perhaps understandable that WW felt that this area is not yet ripe for a man-in-the-street book.[4]

7. *Policy Implications*

These issues are intellectually fascinating and challenging, but ultimately we are interested in them because we want to provide a framework for policy analysis. Are we there yet, and how do these two books contribute?

Some analysts see the need for immediate and strong action to reduce GHG emissions (Stern for example), whereas others are noticeably more relaxed (Nordhaus). These differences can generally be traced back to two sources: different choices of discount rate, and different damage functions. Stern uses a lower discount rate than Nordhaus, and assumes far greater damages: these are sufficient to explain the different conclusions. Both base their conclusions on integrated assessment models: are these models good enough to carry such weight?

As I've already indicated, I'm not a believer when it comes to numerical conclusions from IAMs: I think these models have a role to play in exploring qualitative relationships in complex systems and getting some idea of the orders of magnitude of important interactions, but there is too much uncertainty about the key relationships to take numerical outputs seriously. But I think that in spite of this, it is possible to justify strong action to abate greenhouse gas emissions.

What is the nature of the argument in favor of strong action? It's basically the one in Wagner and Weitzman: it's a risk-management argument based on the tail risks associated with possible changes in GMST, not one focused on the most likely outcomes. There is a probability, between 2 percent and 10 percent, that GMST this century could rise by about six degrees

[4] To be fair, they refer to this work in their table 3.2 on p. 67.

Celsius (see figure 1). This is not the most likely outcome, but it *is* an outcome with a nonnegligible probability. The consequences of a temperature increase of this magnitude, while not known with certainty, are likely to be disastrous, posing a challenge to our entire way of life. A chance somewhere in the 2–10 percent range of a disaster is a risk that no one should take if they can avoid it—it's almost as bad as playing Russian roulette. And we can avoid it, and indeed can do so at a relatively modest cost.

The cost of avoiding climate change is the cost of switching from fossil to noncarbon energy sources. In practical terms, this means moving from burning coal and gas to generating the great majority of our electricity from renewable sources or nuclear power, or some combination of the two. It also means replacing gasoline and diesel as sources of energy in transportation.

Replacing fossil fuels in power generation is looking far more feasible and far less costly today than it did a decade ago. The costs of power from wind and solar PV have declined dramatically, and are now competitive or close to competitive with fossil fuels. The following table shows numbers for electricity costs from various sources from Lazards:[5]

Power Source	**Lazard LCOE**
Wind	\$32–\$62/mWh
Solar PV[6]	\$46–\$56/mWh
Gas Peaking	\$165–\$217/mWh
Gas Combined Cycle	\$48–\$78/mWh
Coal IGCC[7]	\$94–\$210/mWh
Coal	\$60–\$143/mWh

These costs do not take into account any social costs not paid by the producer, and also omit transmission costs and costs associated with the need to back up intermittent plants, which can add \$5–\$10/mWh to wind or solar costs and generally necessitate the maintenance of spare gas-fired capacity. These costs also do not reflect the impact of government subsidies. This is not the place to discuss these numbers in great detail: the point is just that wind and solar can be competitive with any fossil fuel. Another five years of price decreases or a modest carbon tax or other emissions penalty would tip the balance completely against gas and coal. So the costs of switching from fossil fuels to alternatives in electric power generation are bounded: the United States consumes about four billion mWh annually, so if the cost of each is raised by \$20—a worst case from the above figures—the extra cost is \$80 billion annually. The LCOE includes both capital and operating costs, so this figure is the annualized equivalent of all costs of the transition from fossil fuels in power generation. (For a more detailed analysis, see Heal forthcoming.)

Probably the biggest obstacle to the widespread adoption of renewable energy now is not cost but its intermittency and the need to work around this. Intermittency cries out for energy-storage technologies, and this is a rapidly expanding field, but one that is only now beginning to provide economically attractive ways of smoothing the output of intermittent power sources. (Heal 2016 reviews the economics of energy storage.)

Replacing fossil fuels in transportation is a more difficult task, but developers of electric and hybrid vehicles are making a start. Of course, unless the power that charges them comes from nonfossil sources, electric vehicles are only a minor improvement over internal combustion engines (Holland et al. 2015). The biggest obstacle to the market success of electric vehicles currently seems to be battery technology—in fact, the same energy-storage problem that limits the spread of renewable energy.

Returning to the two books under discussion, *Climate Shock: The Economic*

[5] http://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf

[6] Photovoltaic.

[7] Integrated gasification combined cycle.

Consequences of a Hotter Planet does a great job of setting out the case for action on climate, although it says less than I would like about the falling costs of such action. *Sustainability for a Warming Planet* is a more reflective and scholarly book, not a call to action but an intelligent and original analysis of the economic and philosophical issues underlying the climate problem. It concludes that we can meet the world's two-degree Celsius target while continuing to grow and meet international political constraints, which is both encouraging and an implicit call to action.

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