Uncertainty and Climate Change

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Abstract

Uncertainty is pervasive in analysis of climate change. How should economists allow for this? And how have they allowed for it? This paper reviews both of these questions.

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1 Overview

The extent to which the earth's climate will change as a result of human activity is still unclear. Although the basic science is well-understood and now seems confirmed by the data available, the precise magnitudes of the various effects that contribute to the climate regime are not yet known. The most recent assessment by the UN Intergovernmental Panel on Climate Change (IPCC), the Third Assessment Report (TAR), has for the first time made an explicit attempt to give an indication of the degrees of uncertainty associated with its various predictions.[1] The TAR gives an indication of the degree of confidence that the leading authorities in the field of climate change have in their forecasts. In some cases it is clear that, while the sign of an impact is clearly known, there remains massive uncertainty about the size, with the range of possible magnitudes involving differences of several hundred percent. This is illustrated by the IPCC's widely-quoted range for the possible change in

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[1] An earlier review of the extent and nature of uncertainty in climate forecasting can be found in Roughgarden and Schneider (1999).

global mean temperature, which goes from 1.5 to 6 degrees centigrade.[2] In the TAR the IPCC classifies its findings according to the degree of confidence in them. It recognizes five different confidence levels, ranging from "very high (>95%)" through "high (67<X<95%)" and "medium (33<X<67%)" to "very low (<5%)". Most of its major findings are assigned one of these probability rankings, which in general are assumed to correspond to Bayesian subjective probabilities. In cases in which a Bayesian characterization is considered inappropriate, largely because the state of knowledge is too primitive, the IPCC TAR uses a four-way classification:

		Amount of evidence (observations, model output, theory, etc.)	
		Low	High
Level of agreement	High	Established but incomplete	Well-established
	Low	Speculative	Competing explanations

Table 1. IPCC TAR classifications.

This classification shows four cases: the most certain is a high level of agreement between scientists and a substantial amount of evidence on the issue, but not enough to distinguish between the competing theories: the opposite case is low agreement about the alternative theories and little evidence to distinguish between them. They characterize this as a situation where the analysis has to be "speculative".

As economists, it is not only uncertainty about the underlying climate science that should be of concern to us. Ultimately we are interested in the impact of climate change on human societies, and this involves knowing not only how the climate may alter but also how changes in the climate regime translate into impacts that matter for humans. How do climate changes translate into changes in agricultural production, into changes in the ranges of disease vectors, into changes in patterns of tourist travel, even into feelings of well-being directly associated with the state of the climate? So we are concerned here about the outcome of a process with at least two stages: stage one is a change in the climate regime and stage two is the translation of this into changes in things that matter directly to us. Even if we knew exactly what the climate would be in 2050, we still would face major economic uncertainties because we currently do not know how altered climate states map into human welfare.

In assessing the economics of climate change there are therefore at least two sources of uncertainty - what the climate will be, and what any given changed climate will mean in economic terms. We can think of these as the scientific uncertainties

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[2] To be fair to the climate science community we should probably think of the change in temperature as a variation in the earth's absolute temperature, which is about 280 degrees Kelvin, so that we are looking at uncertainty that is only a couple of percentage points of the absolute temperature. Mason (1995) provides a perspective on the development of climate modelling. Note that anthropogenic emissions are only a fraction of what is added each year in terms of carbon. This does not simplify the task of predicting the consequences for the climate of human-made carbon reductions that are likely to be some fraction of current emissions.

analyzed by the IPCC's TAR, and the uncertainties about climate impacts. In fact there is a third stage, uncertainty about the policies that we will choose to control emissions over the coming decades. So in trying to forecast what the climate will be at a future date such as 2050 we have not only to forecast how the climate system will respond to human influence but also what that influence will be: what policies will be chosen in the interim.

In total, we seem to have to take account of scientific uncertainty, impact uncertainty and policy uncertainty. Possible policy responses to climate change take two forms: *mitigation*, i.e., actions that reduce the flow of greenhouse gases into the atmosphere and, thereby, change the probability distribution over future climate states; and *adaptation* – actions that reduce the damages associated with a given climate state.[3] Both provide sources of uncertainty. In the domain of mitigation, perhaps the most prominent source of uncertainty is institutional: will the international community adopt aggressive mandates to restrict emissions of greenhouse gases? Will the institutions that implement these mandates be efficient, i.e., will the marginal cost of net reductions in emissions be roughly equal across all sources and sinks? What technical changes will appear to reduce the costs of mitigation? Adaptation likewise involves uncertainty about the different options that will become available, and their costs.

The IPCC TAR goes further and recognizes no less than five stages of uncertainty, as a result of breaking down the scientific uncertainty into sub categories. Its five categories are uncertainty about emission scenarios (i.e. about anthropogenic emissions of greenhouse gases), about the responses of the carbon cycle to these emissions, about the sensitivity of the climate to changes in the carbon cycle, about the regional implications of a global climate scenario, and finally uncertainty about the possible impacts on human societies. We have noted the first of these - uncertainty about emissions scenarios. And we aggregate the next three (concerning the response of the carbon cycle, the sensitivity of the climate system and the regional implications of global scenarios) as these are all "scientific uncertainty" from the perspective of an economist. This leaves the final category of uncertainty as impacts.The TAR has a diagram that shows the degree of uncertainty rising as we move through these five stages, with the error bars growing from stage to stage.

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[3] Interestingly, the first two IPCC Assessment Reports did not discuss adaptation. This omission has been attributed to political pressure from the environmental lobby. As the Columbia sociologist Steve Rayner has quipped, "Environmentalists don't want to talk about adaptation for the same reason Southern Baptists don't want to talk about birth control," i.e., out of concern that the act of talking about these measures might be construed as an acceptance of the sinful behavior leading to their necessity. See Kane and Shogren (2000) for a summary on adaption and mitigation arguments. They make the important point that adaption and mitigation are linked. Indeed, the Kyoto-protocol posits world-wide (but not global) mitigation efforts. Combining mitigation and adaption, however, would seem to afford the same climate improvement at lesser cost. They also note that attempts to "assess risk levels solely in terms of natural science may be misleading and costly; adaption and mitigation are endogenous to the integrated system..."

Uncertainty can of course be reduced through learning. This consideration leads to a second-order, or meta- form of uncertainty: what new information will be revealed to resolve the present uncertainties? To what extent can and will research accelerate the pace of learning? Given the possibility of future learning, issues of irreversibility and quasi-option value may become salient. This discussion suggests clearly that any economic analysis of climate change should include uncertainty as a central feature. Yet a review of the literature shows that the bulk of the work to date has been deterministic, though there are exceptions and the trend is changing. If uncertainty is central then attitudes towards risk and the degree of risk aversion will presumably be central parameters. Institutions for risk-shifting will also be important, and the possibility that some changes are irreversible and that we may learn more about them with the passage of time suggests that real option values may also matter in the analysis of policy measures. Another analytically interesting feature of climate change is that the risks are not exogenous, as in many models of uncertainty in economics, but are generated by our own activities. This endogeneity of the risks raises questions about the use of markets and insurance for hedging some of the risks associated with possible climate change: there is the macro-level equivalent of moral hazard here. Finally, as many authors have remarked, the time horizon implicit in climate change is very long indeed, measured in centuries, far longer than economists are used to. Uncertainties are almost inevitably large when decisions involve such long time horizons. In sum: in analyzing climate change policies, attitudes towards risk will be important, as may be the values of maintaining certain options open.

Endogeneity of risks may pose some problems for the use of certain types of financial institutions, and the length of the time horizon will pose a challenge to our normal ideas about discounting.[4] As the preceding discussion indicates, the economic problem of climate management cleaves (usefully, if imperfectly) into four parts. Section 2 summarizes what climate scientists can tell us about the main sources of uncertainty in the relationship between greenhouse gas emissions and future climate states. Section 3 addresses the relationship between future climate states and impacts on human welfare. Section 4 sets out the basic economic issues, and summarizes some calculations indicative of the possible importance of key economic parameters. In section 4 we set out a very general model that seems to incorporate most of the central issues. This model is too complex to be solved analytically, and we then review the models that have actually been solved to date, most of which can be seen as special cases of this framework. In subsequent sections we look at a range of issues relating to the management of climate risks by economic institutions such as financial markets, and the impact of uncertainty and the endogeneity of risks on these institutions.

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[4] For a recent summary of the environmental economics literature on endogenous risk, see Crocker and Shogren (2003).

2 Uncertainty in the TAR

To set the stage, we begin by surveying the area where economics has the least direct relevance: understanding the relationship between greenhouse gas buildup and possible future climate states. What can the scientific community tell us about these relationships, and with what degree of certainty? The basic physics of climate change is well-understood and not controversial, and has been known for over a century. Uncertainties arise when applying the physical principles via complex computer models with many parameters that have to be estimated or calibrated from inadequate data sets. These are issues to which economists can surely relate!

So most of the central numerical estimates are subject to considerable error, as indicated by the flagship prediction of the IPCC that global mean temperature will change by between 1.5 and 6 degrees centigrade by 2100 relative to 1990 - a difference of a factor of four between the top and bottom of the range. To be fair we have to recall that this is a 100 year forecast - how many economists would want to put their names to forecasts for 2100? Probably we would find that the range of social and economic uncertainties is even greater if we were to think about it. Many of the uncertainties that appear in the forecasts arise naturally from the length of the time horizon considered combined with the uncertainties in the model parameters. Specific issues that make an additional contribution to uncertainty include the impacts of aerosols - fine particles in the air often caused by pollution - on the condensation of water vapor and the formation of clouds, and more generally the formation of clouds. Clouds reflect sunlight back into space and so control warming to some degree, and little is understood numerically about their formation, though it is known that fine particles in the air provide nuclei on which water droplets can form and start the process of cloud formation. A rather different source of uncertainty is the possible failure of the thermohaline circulation system in the north Atlantic: this is the technical name for the Gulf Stream that brings hot water from the tropical regions to northern Europe. This massive heat transfer is largely responsible for the comparatively benign climate of northern Europe relative to those of other regions at the same latitude, and there is evidence that during past climate fluctuations this system has stopped, leading to massive cooling in Europe. Computer models do indicate that atmospheric warming by greenhouse gases could switch off this massive heat transfer system, with dramatic results for the climates of many densely populated regions.[5]

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[5] A numerical analysis of the economics of a potential collapse of the thermohaline circulation system, using a modified cversion of DICE (Nordhaus (1994)), is in Keller, Tan, Morel, and Bradford (2000). An expanded version of this work that also include e.g. learning effects, arrives at the same conclusion, namely that significant reductions of carbon emissions may be worthwhile. See Keller, K. , Bolker, B.M. and D.F. Bradford, ”Uncertain Thresholds and Economic Optimal Growth”. www.princeton.edu/~bradford/kellerbolker.pdf. This is to be compared with several well-known empirical models, DICE is an example, that predict rather modest costs of climate change. More on this later in the paper.

However, the IPCC assigns a “low” probability to this. The fact that something is a low probability event does not of course mean that it does not matter economically - if the consequences are sufficiently dramatic then this may more than compensate for the low likelihood and mean that the expected loss is still significant. So the IPCC’s comment that something is “low probability” does not mean that as social scientists we should neglect it; this depends on the consequences. Other issues that are still not resolved at the scientific level concern the behavior of terrestrial carbon sinks at higher temperatures and carbon dioxide concentrations, and also the behavior of the oceans both as heat sinks and as carbon sinks. As the oceans sequester more carbon than the terrestrial biosphere and are a major element in the planet’s heat transfer system, this lack of detailed understanding translates into a significant source of uncertainty.

3 Climate change and human welfare

Changes in climate have effects on human welfare through many pathways. To date most studies have considered the impact of climate change on agricultural productivity and on sea level and indeed have more or less equated the overall impact of climate change with these impacts. We are beginning to see that this is probably a very restricted and limited view of climate change and its human impacts. There are suggestions emerging that climate has an impact on economic development and on the pattern of economic growth. There are also suggestions that climate affects human welfare directly, not via agricultural output or economic development but as an argument of the utility function. Climate changes will also affect the occurrence of extreme events and the geographical range of many disease vectors such as the malarial pathogens.

David Landes (1998) includes climate as one of the key factors in his widely read (and controversial) “The Wealth and Poverty of Nations”. Tropical diseases, access to water, the propensity to natural disasters, etc. present regions like Africa with a handicap, according to Landes. He also presents an account of geographers and others who marshalled climate as the key variable to explain economic differences. In a similar vein is a recent study by Horowitz (2001) . He carried out a regression that addresses the relationship across countries between average annual temperature and GDP per head, looking at the income-temperature relationship for a cross-section of 156 countries in 1999. As is well known, hotter countries are poorer on average. The widespread belief is that this relationship is mostly historical; that is, due to a past effect of climate. Acemoglu, Johnson, and Robinson (2001) have recently made great gains in identifying a specific historical path for this relationship. They posit that mortality rates of early colonizing settlers had a profound effect on the institutions that were set up in those colonies. These institutional differences persist to this day, they argue, and have strong effects on current incomes. Because colonial mortality and average temperature are highly correlated, the mortality-income relationship also manifests itself as an income-temperature relationship. Horowitz argues that there is, however, sufficient evidence to warrant continued examination of the income-temperature relationship. He finds a strong income-temperature relationship within OECD countries, a result that does not appear to be predicted by the colonial mortality model. He also finds that the income-temperature relationship is essentially the same within the OECD and non-OECD countries, a striking yet unremarked and as-yet unexplained result. Finally he finds a strong income-temperature relationship within the fifteen countries of the former Soviet Union, where colonial institutions would seem to have been wiped out. His best measure of the effect of temperature on income, after accounting for the influence of colonial mortality, is that a one percent increase in temperature leads to a -0.9 percent decrease in per capita income. Thus, a temperature increase of 3 degrees Fahrenheit would result in a 4.6 percent decrease in world GNP. The result is striking. While the result is only suggestive – there is no causal mechanism offered – it suggests that there is a relationship between temperature and economic production, and that changes in temperature may, then, create first-order changes in economic output and welfare.

Similar conclusions are emerging from other related studies. Gallup, Sachs and Mellinger (1998) have suggested that tropical climates make economic development more difficult, via reduced agricultural productivity and added disease burden. They do not specifically comment on the economic consequences of climate change but an implication of their findings is surely that as "tropical" climates become more widespread then so will their economic disadvantages. Similar conclusions are suggested by Gavin and Hausman (1998). All of the results that tie climate to economic development are tentative and are too preliminary to form the basis for quantitative estimates of welfare impacts. They represent a mechanism through which climate change can have economic consequences which has been little explored to date, and consequently is a source of uncertainty in any estimates of climate change impacts.

3.1 Direct effects on human well-being

There is a clear connection between weather, climate, and how well people feel. We dislike very cold climates and very hot ones, and possibly also very humid ones. There are probably good reasons for these likes and dislikes, founded in evolutionary biology. In this context, Maddison and Bigano (2000) find that the most popular tourist destinations are those offering temperatures of around 88°F (31° C): this appears to be an "ideal temperature", at least for the inhabitants of western Europe. Lise and Tol (2001) find similar results. They carry out a cross-section analysis on destinations of OECD tourists and a factor and regression analysis on holiday activities of Dutch tourists, to find optimal temperatures at travel destination for different tourists and different tourist activities. Globally, OECD tourists prefer a temperature of 21°C (= 70 F) (average of the hottest month of the year) at their choice of holiday destination. This finding and Maddison's results indicate that, under a scenario of gradual warming, tourists would spend their holidays in different places than they currently do. It also suggests that as temperatures change as a result of global warming there could be a loss of welfare in some regions just because of the climate change itself and quite independently of any consequences for economic activity.

It seems a very safe assumption that human preferences about temperature are biologically determined and are likely, therefore, to be stable over time. This is not to deny that temperature preferences may well exhibit cross-sectional variation across cultures and ethnic groups. Insofar as people are biologically or culturally adapted to particular climes, change may be bad per se. In some sense this is just an extension of the argument that plants and animals that are adapted to certain climate conditions will suffer from climate change. Humans are just one of many species of animals, albeit an unusually disruptive one, and so in principle are subject to the same effects. The direct effects of climate on human welfare are probably the least explored of all effects so far, and could be some of the more important, especially for populations in areas where agriculture will not be greatly affected by a changed climate regime. They are therefore a major source of uncertainty.

4 The economic framework

That discount rates and attitudes to the far future matter in assessing climate change has always been clear. Now it should also be clear that risk aversion will matter as well. An important implication of this is that even though an event is very unlikely, if it is costly and we are risk averse we may invest significantly in avoiding it or insuring against it. By way of illustration, our houses rarely burn down, yet most of us insure them against this event on terms that are actuarially unfair.

In the context of climate change there is a real potential for learning over time. Global circulation models have been greatly refined and enhanced since their first use in analyzing climate change, and this has improved our understanding of what might happen. There are many other ways in which our understanding might improve in the future. We might learn about cleaner energy production technologies, or about novel methods of carbon sequestration. Over several decades the changes in our understanding of these possibilities could be far-reaching. Significant changes in our understanding of these possibilities could alter the relative merits of different economic policies. As an illustration, Lackner et al. (1999) have proposed the sequestration of carbon dioxide by using calcium hydroxide, and the scrubbing of emission gases from fossil fuel plants using the same chemical (spraying tropical waters with iron filings is another geoengineering suggestion, see Keith (2000) for a review). The possibility of implementing this on a large scale is still speculative and will remain so for some years, but this discussion offers a tantalizing glimpse of the kind of qualitative technological change that might occur within the next few decades.

4.1 Irreversibility

It is also likely that many of the changes in climate, and changes in the natural environment driven by climate change, will be irreversible. The consequences of this possible irreversibility have been discussed at great length, if rather inconclusively, so it is important to understand the underlying issues. Changes in the climate may in themselves be irreversible: once the climate regime in an area has changed, it may not be possible to restore the original. The most notable case of this arises from the possible change in the path of the Gulf Stream, a possibility that we mentioned as one of the biggest sources of uncertainty in forecasting climate regimes. The issue here is that the climate system is a complex nonlinear dynamical system and like most such systems has several possible equilibrium states or attractors. Each has a basin of attraction - a set of initial conditions within which it is stable, in the sense that if the initial conditions are within the basin then the system moves to that equilibrium. Stresses on the system, such as human changes to the mix of gases in the atmosphere, could possibly move the climate system from one basin of attraction to another. Moving from one configuration of the Gulf Stream to another would be an example of this. Once the system is in a new basin of attraction it is not obvious that we could move it back to the original, so such a change may be irreversible.

Possible irreversibilities may also arise because the climate is determined by interactions between the atmosphere, the oceans and the biosphere. Changes in the climate might lead to changes in oceans or the biosphere that would make the restoration of the original configuration impossible. For example, the climate of the Amazonian region is created in part by the forests there; trees in the forest transpire vast quantities of moisture into the air and contribute to the humidity of the region. Were the region to become hotter and drier, these trees would die and consequently the soils would change. Reducing the concentration of greenhouse gases in the atmosphere would then probably not restore the original climate to the Amazonian region because the forest would have died and could not be restarted, and was a key element of the original climate system. Another irreversible aspect of climate change would be the melting of the west antarctic ice sheet, which would lead to a significant and rapid increase in sea levels globally.

Issues of how far climate changes could be reversed by reducing greenhouse gas concentrations have not been extensively studied, although in most economic models processes are modelled as if the changes in climate can eventually be reversed, even if slowly. Even if changes in the climate were to be reversible, there are other associated changes that might not be. For example, climate changes might drive certain species extinct if their habitats are destroyed: indeed increased extinction rates are a widely-forecast consequence of climate change. Extinction is self-evidently not a reversible process. At a more mundane level, climate change will alter plant and animal communities in ways that may make it impossible to reestablish the original community even if the components are not extinct. In this vein, an expected consequence of climate change is the death of some coral reefs. This will lead to changes in marine communities that will not be reversible on human timescales. This combination of potential for learning together with irreversibilities is the classical breeding ground for real option values. If climate change or its consequences are indeed irreversible and there is a chance of learning more over time, then there may be a real option value associated with preserving the present climate regime, i.e. with freezing all actions that are likely to contribute to climate change. This real option value could reinforce the widely-cited but seldom analyzed "precautionary principle," a nostrum to the effect that we should avoid making possible environmental changes until we are sure of their consequences. However, confusingly, there is another possible real option value at work here. Suppose that substantial sunk costs must be incurred to begin the process of abating greenhouse gas emission and avoiding or minimizing climate change. The return to this investment is the avoidance of climate change and if we learn about the value of this over time then there is also a real option value associated with postponing investment in greenhouse gas abatement. So there could also be an "inverse precautionary principle" at work here suggesting that we avoid costly policies requiring irreversible investments until we are really sure that they are needed.

Striking a balance here is made more complex by the fact that it is not only the time horizons that are long, but also the time lags in many parts of the system. Both climate and economic systems are likely to respond very slowly to policies implemented to change greenhouse gas emissions. So even if a forceful greenhouse gas abatement policy were implemented tomorrow, its impact might not be felt on emission levels until 2010 or later, and the consequences for the climate of a reduction in GHG flows beginning in 2010 or later would be slight prior to 2020 at the very earliest. There would be further lags between changes in climate trends and the trends in the factors that affect humans - agriculture, diseases, etc. Consequently there is an argument that as there is a real risk that the climate will be seriously perturbed by human action by say 2040, and as the lags in the systems that link our policies to the outcomes that matter are so long, then we have a responsibility to start taking actions now, as actions taken later will be too late to avoid harm to those living in 2040.

By now it is clear that setting out a convincing analytical framework for climate policy choices is a challenge: the intrinsic uncertainties enter in many different ways. Next we take a look at how these issues could in principle be captured, and how they have actually been captured, in the literature to date.

4.2 Preliminary calculations: the value of avoiding climate change

Before developing a general framework and reviewing the literature, which is the main purpose of this paper, we review some simple yet suggestive calculations that indicate the importance of allowing for uncertainty in the economics of climate change.

These calculations were addressed to the question: what costs is it worth incurring to avoid the risk of climate change? Within a simple framework we can carry out calculations that illustrate the issues involved, and how discount rates, risk aversion and probabilities interact. The answer depends on the following four parameters, of which two are clearly economic:

(1) the probability distribution of the effects of climate change,

(2) the degree to which we are risk averse,

(3) the date at which the climate change will occur, and

(4) the rate at which we discount future benefits and costs relative to those in the present.

How exactly might we compute what it might be rational to pay to avoid the risks of climate change?[6] Denote society's income in the absence of climate change by I and the benefits derived from this income by utility $u(I)$. Utility is taken to be a function of I that increases at a decreasing rate. The expected utility after climate change is $\sum_j p_j u(I_j)$.[7] Climate change occurs, if it occurs at all, in year C. Denote by $\delta \leq 1$ the weight given to costs or benefits at date $t+1$ relative to those at t, so that δ^{t-1} is the weight given to those at t relative to those at 1. Then $(1-\delta) \times 100$ is the discount rate as a percent.

Suppose that it possible by incurring a cost from now to the date C at which climate change might occur, to rule out this occurrence. What cost x is it worth our while incurring, from now to C, in order to ensure that the climate does not change at C? The number x that we seek is the solution to the equation

$$\sum_{t=1}^{C} \delta^{t-1} \left[u(I) - u(I-x)\right] = \sum_{t=C+1}^{T} \delta^{t-1} \left[u(I) - \sum_j p_j u(I_j)\right] \qquad (1)$$

The left hand side is the loss of utility in incurring the cost x from now to the time C of climate change, with future losses discounted back to the present: the loss each year is $[u(I) - u(I-x)]$, and we sum this, discounted, over all years up to C. The right hand side is what we would lose each year, in expected value terms, if climate change were to occur, summed from its occurrence at C to a distant date T, and again discounted to the present. The expected annual loss is $\left[u(I) - \sum_j p_j u(I_j)\right]$. This sum on the right is therefore also the benefit of avoiding climate change. The maximum we should be willing to pay is the value of x at which these two are equal: hence the equation. The date T is the maximum time horizon that we consider relevant to these calculations.

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[6] The calculations that follow are taken from work in progress by Geoffrey Heal and Yun Lin, Columbia University.

[7] If there is climate change, then income drops from I to I_j with probability p_j, where clearly $I_j \leq I$ and $\sum_j p_j \leq 1$. This can be weakened to allow an income drop on the average, in order to include a possibility for income increases. With risk aversion, people would still be willing to pay to avoid the change. Thanks to Mark Machina for pointing this out.

As a concrete illustration, we can think of x as the extra cost of moving as fast as possible to energy based on non-fossil sources, such as solar, geothermal or biomass. As these technologies develop, this cost will decline: we assume that it is zero by the time at which climate change would occur, which in the illustrative calculations is taken to be fifty years hence. Obviously there are some heroic assumptions here. Climate change is taken to be a discrete event. Preventive expenditures are assumed to be constant. But nevertheless the numbers are interesting.

4.2.1 Results

Below we present values of x for some illustrative parameter values and indicate their sensitivity to the assumptions. What we should be willing to pay, x, is expressed as a percent of the income level[8] I, which is taken to be 10. The calculations are only illustrative: we do not know enough about the costs or probabilities of climate change to make presenting a best estimate of x a useful exercise. The key conclusion is that for some parameter values that must be within the set considered possible, one might wish to spend up to 8.13% of national income on avoiding climate change. For other parameter values that are also possible, the number may be 0.1%. Even this is a big number in absolute terms. The most critical parameter in these calculations is an economic parameter, the discount rate, which rarely features in policy discussions. The index of risk aversion is also very influential.

A reasonable functional form for the utility functions $u(I)$, widely used in empirical studies of behavior under uncertainty, is the family of functions displaying constant relative risk aversion: the index of relative risk aversion (IRRA) for $u(I)$ at income I is $-Iu''/u'$ where u' and u'' are the first and second derivatives of u respectively. This is a measure of willingness to pay to avoid risk. Functions for which this index is constant are of the form I^a for $a > 0$, $-I^a$ for $a < 0$, and $\log(I)$. A reasonable range of empirical values for the index of relative risk aversion is from 2 to 6.

Tables 3, 4 and 5 report the values of x in the equation above for alternative combinations of the discount rate in percent, denoted δ, and the index of relative risks aversion. Each table corresponds to a different probability distribution of the impacts of climate change: these distributions are called A, B and C and summarized in table 2. In the first of these, there is a 20% chance of a loss of income of five percent, a 10% chance of an income loss of 15% and a 5% chance of a loss of 25% as a result of global warming. By implication, there is a 65% chance of no loss at all, and the expected loss is 3.75% of current income. This figure for the expected loss is generally consistent with the IPCC estimate of the loss from climate change. The other two cases are more conservative: the possible losses are lower and the probabilities are concentrated more at the low end of the distribution. In the most conservative case, the expected loss is fractionally under 1% of income, with a probability of 0.24 of an

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[8] Because of the choice of functions for which the IRRA is constant, the ratio x/I is independent of the value of I, so that we do not need to think hard in choosing a value for I.

income loss of 2%, a probability of 0.10 of a loss of 5% and a probability of 0.01 of a loss of 10%.[9]

	Probability		
Loss	A	B	C
2%			0.24
5%	0.2	0.24	0.1
10%			0.01
15%	0.1	0.10	
20%		0.01	
25%	0.05		
0	0.65	0.65	0.65
E. Loss	3.75%	2.99%	0.99%

Table 2: alternative probability distributions.

As mentioned, the date for climate change C is assumed to be fifty years, and we take the upper limit of the sum of benefits T to be 1000.

The following tables reports the results of solving the equation for x for these probability distributions and a range values for the discount rate (from 1% to 5%) and for the IRRA (from 0 to 6).

IRRA	0	1	2	3	4	5	6
δ							
1	5.74	6.07	6.42	6.81	7.22	7.66	8.13
2	2.15	2.32	2.50	2.72	2.96	3.23	3.54
3	1.05	1.13	1.23	1.35	1.48	1.64	1.82
4	0.56	0.61	0.66	0.73	0.81	0.89	1.00
5	0.31	0.34	0.37	0.41	0.45	0.50	0.56

Table 3: willingness-to-pay for distribution A.

IRRA	0	1	2	3	4	5	6
δ							
1	4.44	4.61	4.78	4.96	5.15	5.35	5.56
2	1.66	1.75	1.84	1.95	2.06	2.18	2.31
3	0.81	0.86	0.91	0.96	1.02	1.09	1.16
4	0.43	0.46	0.49	0.51	0.55	0.59	0.63
5	0.24	0.26	0.27	0.29	0.31	0.33	0.36

Table 4: willingness-to-pay for distribution B.

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[9] For an interesting review of the available evidence on the probabilities of loss from climate change see Roughgarden and Schneider (1999), who take a range of expert opinions and fit a systematic probability density function to these. Geoffrey Heal is in the process of recomputing this model with the probability-of-loss function given in Roughgarden and Schneider (1999).

IRRA	0	1	2	3	4	5	6
δ							
1	1.65	1.68	1.70	1.72	1.74	1.77	1.79
2	0.62	0.63	0.64	0.65	0.67	0.68	0.69
3	0.30	0.30	0.31	0.32	0.33	0.33	0.34
4	0.16	0.16	0.17	0.17	0.18	0.18	0.18
5	0.09	0.09	0.09	0.10	0.10	0.10	0.10

Table 5: willingness-to-pay for distribution C.

Can we pin down more precisely the most appropriate parameter ranges? The question of risk aversion has not been studied in the context of climate change. However there are many empirical studies of risk aversion in finance, and the range of values for the IRRA considered to be appropriate there runs from 2 to 6. The issue of the right discount rate is a controversial one: one of the founders of dynamics economics, Frank Ramsey (1928) declared in a paper that is still in many ways definitive that "discounting of future utilities is unethical, and arises purely from a weakness of the imagination."[10] This implies a discount rate of zero, which in turn implies a willingness to spend from 15% to 30% of income to prevent global warming. Most contemporary commentators have implicitly disagreed with Ramsey, in many cases without clearly stating their reasons, and for the very long time horizons involved in climate change have worked with discount rates of 1% or 2%.[11] The table makes it clear that the choice of a discount rate is critical: a general sensitivity analysis confirms that within the range of reasonable parameters and functional forms, this is the central parameter. It is clear that for fifty to one hundred years ahead, discount rates of 5%, 4% and 3% give almost no present value. At these rates, climate change simply does not matter: it occurs on a time frame which such discount rates value at less than ten cents in the dollar. Hence the general presumption that lower discount rates are appropriate. Weitzman (1998) reports an interesting survey of the opinions of 1,720 economists on this issue: their median response for the appropriate discount rate to be used in problems relating to global warming is 2% and the mean 4%±3%.[12]

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[10] As Arrow (1995, p. 16) points out, however: "When Ramsey was in a less moral mode he in fact agreed [that the pure rate of time preference is positive]". Arrow refers to Ramsey (1931, p. 291).

[11] For a general discussion of these issues, see Heal (1998). Cline (1992) is an empirical study that indicates the sensitivity of a choice to the discount rate.

[12] Weitzman asks for a constant discount rate, although as Heal (1998) points out, the consumption discount rate is not necessarily constant over the time spans considered (several centuries). This follows from the Euler equation of a standard Ramsey problem. A slowing down of economic growth entails, for example, a lower consumption discount rate, if the utility discount rate is taken to be constant (in a steady-state the consumption discount rate and the utility discount rate are equal). In this view, it becomes difficult to state the discount rate for long-run, large, projects.

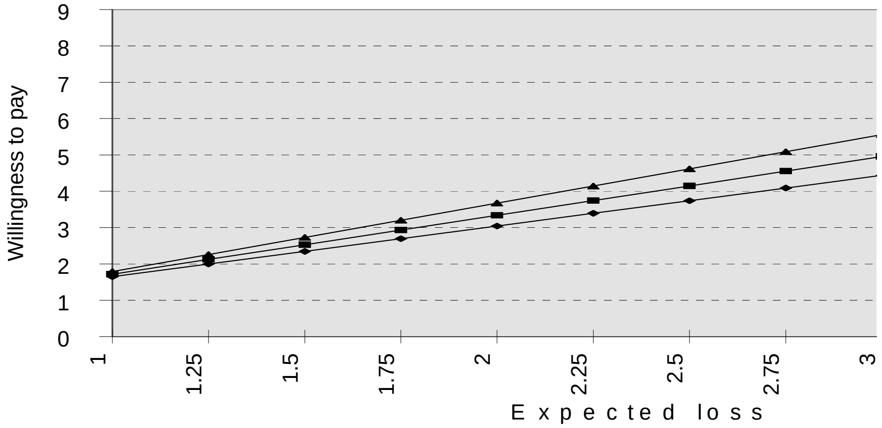

Figure 1:

Another interesting possibility, not investigated here, is the use of a non-constant discount rate, through logarithmic or hyperbolic discounting (see Heal (1998, chapter 5) and references therein). These approaches apply discount rates that are lower, the further into the future the costs and benefits are. There is now a significant amount of evidence that this is the way in which people behave when making intertemporal decisions. Applying this approach leads to a very significant increase in the amount that society should be willing to pay to avoid climate change.

Intuitively, one would expect sensitivity to the magnitude of the expected loss to be important. The three probability distributions, A, B and C give some indication of this, which is summarized in figure 1, which shows willingness-to-pay in % of income versus expected loss in % of income for three different combinations of discount rate and IRRA. In each case the discount rate is 1% and the IRRA values used are 0, 3 and 6. Willingness to pay increases more than linearly with expected loss, with the non-linearity increasing with the IRRA[13]. Both willingness-to-pay and expected loss are expressed as a fraction of income, and in general the willingness-to-pay exceeds the expected loss, a natural result of risk aversion.

Figure 1. Willingness-to-pay in % of income versus expected loss in % of income for three different combinations of discount rate and IRRA

4.3 Risk and climate change

Note that discount rates and attitudes towards risk are to some degree culture specific: different cultures exhibit quite different degrees of future-orientation and of risk

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[13] Note that only three points on each curve are "real", those corresponding to expected losses of 1%, 3% and 3.75%: the rest are interpolations.

tolerance. The US, for example, is often characterized as a society with a high level of impatience (a high discount rate) and a high level of risk tolerance (a low IRRA). Europe and Japan are placed by the same observers at the other end of the spectrum. If this is correct, and different countries really value avoiding climate change differently, then there is scope for trade between them (see Chichilnisky and Heal (1993) for details).

What are the implications of this model? Certainly one would not want to take the numerical conclusions at face value. The point is that uncertainty, risk and our attitudes towards risk really do matter in making policy decisions. They should be taken quite explicitly into account in formulating policy on climate change. Our final policy analysis may be as sensitive to attitudes towards risk as to some aspects of the scientific data which we work so hard to generate. Yet to date we have done little to introduce these issues into the policy debate.

In fact the role of risk and uncertainty in an analysis of policy towards climate change goes much further. There are several dimensions of this role that merit particular comment: these are the endogeneity of the risks that we face, and the fact that the risks are substantially unknown. Endogeneity of the risks is clear from the fact that they are anthropogenic: we create them as a result of our social and economic activity. It is human activity that drives biodiversity loss, climate change and ozone depletion. That the associated risks are substantially unknown is also clear from the brief discussions above. Another difficult characteristic of climate risks is that a large number of people face the same risks - the risks are correlated across large communities. This means that standard insurance models, relying as they do on independent risks, are probably not appropriate as mechanisms for managing the risks. It also means that we cannot argue, as for many risks (following Arrow and Lind (1970)), that at the social level risks can be neglected as they affect individuals and are independent and so in the aggregate cancel out.

5 A general model

Clearly we have to work with a stochastic dynamic model in which the chance of climate change is affected by, and affects, economic activity and welfare. The most natural and widely-used model seems to be an extension of the standard optimal growth model along the following lines. Output is produced from capital stocks and other inputs, primarily labor. The capital stocks should include both physical capital and natural capital, as some of the most important possible impacts of climate change are on the productivity of natural capital, for example on the productivity of land or of fisheries or the value that can be generated from ski resorts. Climate change could affect land values by changing rainfall patterns, changing access to river flow, or changing the range of agricultural pathogens.

The output can as usual be consumed or invested: production also leads to a flow of greenhouse gases that cumulate into a stock. The size of this stock drives the probability of climate change, and so can affect output. The state of the climate can also affect welfare directly, as we may derive well-being from the climate - we may prefer mild dry climates to hot wet ones, for example. And it can affect human health via factors like the range of disease vectors. There is evidence that the range of malaria has increased in parts of the world in response to changes in climate and during El Nino events the ranges of diseases such as Dengue fever appear to vary in response to changed climate conditions. Mathematically we are looking at a system like the following:

$$
\begin{aligned}
c + \dot{K} + \dot{A} + \dot{S} &= f(K, G) &(2)\\
u &= u(c, G) &(3)\\
\dot{G} &= e(K, A) - \sigma(S) &(4)
\end{aligned}
$$

where K is a vector of manufactured and natural capital stocks, c is consumption, G is the stock of greenhouse gases, S is the capital invested in carbon sequestration, A is investment in minimizing greenhouse gas emissions and a dot over a variable denotes a time derivative. Some key functional relationships here, $f(K, G)$, $e(K, A)$ and $u(c, G)$ are known only with some degree of uncertainty, at least as far as the roles of the greenhouse gas stock G and of the abatement capital A are concerned. The dynamics of the greenhouse gas are shown by the third equation and this indicates that accumulations of certain types of capital - manufactured capital K - can affect the output of greenhouse gases. For example, the stock of coal-powered electricity generating plants affects the output of carbon dioxide. This relationship may be moderated by investment in capital A designed to minimize the output of greenhouse gases - for example by investment in plants designed to use fossil fuels more efficiently or to capture greenhouse gases rather than allowing them to escape into the atmosphere. It is also possible to invest in sequestering greenhouse gases, for example by growing forests: the rate of sequestration depends on the capital invested in this activity. For a constant climate regime we clearly need $\dot{G} = 0$ which implies that $e(K, A) = \sigma(S)$, the rates of emission and sequestration are equal.

These considerations lead to a model that in a deterministic context is relatively tractable. Without the complications of uncertainty we would seek to solve the problem:

$$
\begin{aligned}
&\max \int_0^\infty u(c_t, G_t)\, e^{-rt} dt \text{ subject to} &(5)\\
\dot{G}_t &= e(K_t, A_t) - \sigma(S) \text{ and } \dot{K}_t = f(K_t, G_t) - c_t - a - s
\end{aligned}
$$

where $s = \dot{S}$ (the rate of sequestration of greenhouse gases) and $a = \dot{A}$. The discount rate is r. The presence of four state variables - greenhouse gases G, productive capital K, sequestration capital S and GHG mitigation capital A - makes this a complex problem but one that is nevertheless tractable to some degree. We can solve it by writing out the Hamiltonian and then deriving the first order conditions in a completely standard way:

$$\begin{aligned} H &= u\left(c_t, G_t\right) e^{-rt} + \lambda e^{-rt}\left[e\left(K_t, A_t\right) - \sigma\left(S\right)\right] + \\ &\quad \mu e^{-rt}\left[f\left(K_t, G_t\right) - c_t - a - s\right] + \nu e^{-rt}\left[s\right] + \xi e^{-rt}\left[a\right] \end{aligned} \tag{6}$$

From the choice of control variables we have

$$\frac{\partial u}{\partial c} = \mu = \nu = \xi \tag{7}$$

and then the adjoint variables follow the differential equations:

$$\overset{\bullet}{\lambda} - r\lambda = -\frac{\partial u}{\partial G} - \mu\frac{\partial f}{\partial G} \tag{8}$$

$$\overset{\bullet}{\mu} - r\mu = -\lambda\frac{\partial e}{\partial K} - \mu\frac{\partial k}{\partial K} \tag{9}$$

$$\overset{\bullet}{\nu} - r\nu = \lambda\frac{\partial \sigma}{\partial S} \tag{10}$$

$$\overset{\bullet}{\xi} - r\xi = -\lambda\frac{\partial e}{\partial A} \tag{11}$$

We can find a stationary solution to this system and then analyze how it behaves near that solution, establishing at least the local properties of a stationary solution. However, to introduce uncertainty about some of the key functional relationships here - those involving the impact of greenhouse gases on welfare and production, and perhaps the effects of mitigation capital on emissions - would make the overall problem quite intractable.

In model like that just outlined, what is the role of irreversibility? The stock of greenhouse gases G builds up as a result of economic activity. If accumulation were truly irreversible, then we would have the constraint $\overset{\bullet}{G}_t \geq 0$. In fact $\overset{\bullet}{G}_t = e\left(K_t, A_t\right) - \sigma\left(S\right)$: the first term here is non-negative and the second positive. So in principle the stock of greenhouse gases in this model could be reduced. Most models in the literature also have a term like $-\delta G$ in the GHG accumulation equation, representing the natural oxidation of carbon dioxide to other compounds with a half life of about 60 years. So with sequestration and natural decay the accumulation of GHGs is certainly not irreversible, although the timescale of reduction may be long relative to that of accumulation. Nor is anything else in this framework truly irreversible: for example, utility and production both decrease with increases in G but decrease as G falls: there is no irrevocable change in welfare or production because of GHG accumulation. And the abatement capital stock A can be decumulated as there is no non-negativity constraint on its rate of change. This suggests that this model is not ideally suited to capturing all aspects of the problem at hand. We need a framework where there is at least a possibility of a change that cannot be reversed. Some of the models discussed below have this property.

6 Modelling climate change: some findings

Next we review the literature on modelling climate change and the optimal level of investment in the abatement of greenhouse gases. Because of the complexity of the full problem, all the models to date have focussed on one or other of these sources of uncertainty to the exclusion of other aspects of the model, or have simplified the framework to a discrete time two period context.

6.1 Heal

One of the earliest formal models was that of Heal (1984)[14], which looked entirely at the impact of climate change on the economy's productivity and modelled the uncertainty about this in terms of a very simple stochastic process. Heal assumed that the atmosphere has a fixed but unknown capacity to absorb greenhouse gases without change and then changes discretely when this capacity is exceeded. At this point there is a discrete and completely irreversible change in the productivity of the economy's capital stock and in the well-being of its citizens, so this model does capture the irreversibility of climate change. The uncertainty about the future stems from our lack of knowledge of the level of cumulative emissions at which there will be a discrete change in the economic system as a result of changing atmospheric composition. This model is essentially a model of the optimal depletion of an exhaustible resource, such as fossil fuel, augmented by a relationship between cumulative fuel use and the stock of greenhouse gases. This stock triggered a change in economic productivity when it crossed an unknown threshold, a threshold over which we had a probability distribution. This framework retains the key aspects of an optimal depletion model and transforms the problem of managing climate change into one similar to optimal depletion. In view of what we know almost twenty years later about the possible responses of the natural environment and the economy to changing atmospheric composition this framework seems limited but it did provide a rationale for introducing a precautionary motive for reducing the emissions of greenhouse gases and cutting back on the emissions of fossil fuels. The optimal rate of fossil fuel use was seen to decline more rapidly relative to the situation with no climate change by an amount that depended on the index of risk aversion and on the characteristics of the probability distribution over possible thresholds at which the stock of greenhouse gases tips the economy into a less productive mode. Specifically the conditional probability that

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[14] Early related work appears in Cropper (1976) and Dasgupta and Heal (1974).

the threshold would be reached given that it had not yet been was a key parameter: this number was to be added to the discount rate, leading to a more rapid decrease in the rate of fossil fuel use.

A brief summary of this model is as follows. The atmosphere or climate may be in one of two states, A_f and A_u, which are respectively favorable and unfavorable. Once it has reached the unfavorable state it remains there - this is an absorbing state. The possibility of moving from the favorable and initial state to the unfavorable one is endogenous and depends on the cumulative use of fossil fuels to date, representing the emissions of greenhouse gases. Fossil fuel is used at a rate R_t as an input to production along with capital K_t and the climate or atmosphere $A = A_f$ or A_u :

$$Q_t = Q(K_t, R_t, A) = C_t + \dot{K}_t \tag{12}$$

so that output is either invested or consumed, as usual in a growth model. By definition $Q(K_t, R_t, A_f) > Q(K_t, R_t, A_u)$ for all possible values of K and R. Cumulative emissions are denoted by $Z_t = \int_0^t R_\tau d\tau$ with $\dot{Z}_t = R_t$. The climate evolves as follows: there is a date $T > 0$ such that $A = A_f$ for $t < T$ and $A = A_u$ for $t > T$. T is a random variable whose marginal density function has as its argument cumulative emissions of greenhouse gases proxied by cumulative use of fossil fuels: $f = f(Z)$ and the probability that T lies in the interval (t_1, t_2) is

$$\Pr T \in (t_1, t_2) = \int_{Zt_1}^{Zt_2} f(Z_t) dt \tag{13}$$

The overall optimization problem is therefore

$$\max E \int_0^\infty u(C_t) e^{-rt} dt \text{ subject to } \int_0^\infty R_t dt \leq S_0 \text{ and } \dot{K}_t = Q(K_t, R_t, A) - C_t \tag{14}$$

where r is a discount rate and u a utility function.

6.2 Beltratti et al

In a much more recent model, Beltratti et al. (1998) use a similar mathematical framework but focus instead on uncertainty about the relationship between utility and the stock of greenhouse gases. In this model there is again a stock of an exhaustible resource to be depleted over time - think of this as fossil fuel - and in this case the uncertainty is about future preferences for this or for the goods that can be produced from it. There is a chance that at some future date society's preferences for this will change and in particular it will come to be more highly valued. The question then is - what effect does this possible increase in future preference ranking have on the current use rates? In the context of climate change we can think of this as a model of how to conserve current assets, such as natural environments or biodiversity, given that we may value them more in the future than we do now but we are not sure when if ever this change will take place. The analytical connection with the Heal (1984) paper lies in the fact that the basic model is once again an optimal depletion model and uncertainty is again modeled by the possibility of a one time change at an unknown date. The use of an optimal depletion model coupled with this discrete representation of uncertainty as about a one-time occurrence leads to great simplifications relative to alternatives and makes analytical solutions possible The authors incorporate a direct impact of the stock of greenhouse gases on welfare. Beltratti et al. study the emergence of option values in this framework and show that as in the Heal model the conditional probability of change given that it has not yet occurred is a key variable. This model has recently been extended by Brasão and Cunha-e-Sá (1998) and by Ayong Le Kama and Schubert (2001).

6.3 Kelly and Kolstad

Kelly and Kolstad (2001) use a growth model that is a special case of the general framework set out above to investigate two parameters claimed to be of significant importance for climate change predictions: population and productivity growth. The results produced by current integrated assessment models seem to crucially depend on the assumption that both productivity and population growth are slowing down over the next century. Indeed, Kelly and Kolstad claim that integrated assessment models rely on a significant slowdown in population and productivity to solve the climate change problem. An important and apparently robust finding of Kelly and Kolstad is that there is almost a one-to-one correspondence between population and productivity growth assumptions, the degree of climate change, and hence the optimal response to climate change. Uncertainty arises here at a rather fundamental level, as population and productivity are notoriously hard to predict, at least over the time spans of interest.

Kelly and Kolstad use a standard Ramsey-type growth model that includes a climate component. In the calibrated version of the model, they find that climate change has little impact on the steady-state capital stock, using standard assumptions about the values of the key parameters, i.e. a tapering off of population and productivity growth. The reason why the impact of climate change on the steady-state capital stock is “small” is rather intuitive. If labor growth is decreasing, so will be capital growth and subsequently output. This slowdown is “quick enough” according to the calculations; the engine of growth is turned off before the climate change apparatus switches into high gear.

Clearly, what is “too fast” or “too slow” in this context depends critically on the parametrization and the parameter values used. But the authors claim that if there is no growth in (adjusted) labor, temperature increases are virtually zero (only driven by current inertia) and that this is a robust result. On the other hand, if current trends are to be continued, so that the two key parameters are roughly constant, then there are significant impacts on steady-state capital stocks.

Kelly and Kolstad propose that we add a "baby tax" to a carbon-tax, because exogenous population growth is another way of inducing climate change. Given that population growth is exogenous, the "baby tax" should be interpreted as the social net value of one additional person. Moving down the family tree, we see that the birth of one person literally induces carbon emissions indefinitely. Hence the claim that the "baby tax" should be set such that it incorporate damages from emissions in the future. The welfare economics of population growth raises profound questions, not the least empirical ones (how is one to go about placing a value on those yet unborn?). Furthermore, population growth cannot be positive forever, if only for space considerations. Yet the point Kelly and Kolstad make is an important one in understanding the output from the many integrated assessment models in current use.

A policy conclusion that does seem to follow is that laxer climate controls may be defended by pointing to forthcoming demographic problems (the "graying Europe" is a case in point) Bringing uncertainty proper into a model with similar characteristics may turn the Kelly and Kolstad argument on its head, at least according to Pizer (1998), to which we now turn.

6.4 Pizer

Pizer's (1998) model allows for many different states of nature, includes econometric estimates of key technology and preference parameters (rather than "best guesses") and has consistent welfare aggregation of uncertain utilities[15]. A representative consumer maximizes a Von Neumann-Morgenstern utility function within a stochastic growth model that has a climate component (from the DICE-model). The utility function has constant relative risk aversion and a fixed utility discount rate is assumed. Production (Cobb-Douglas technology) is a function of capital and augmented labor. Net labor productivity is related to the costs of controlling damages; essentially a quadratic damage cost function is used (for temperature changes less than about 10 degrees Celsius). Exogenous labor productivity is a random walk (in logarithms). This formulation implies that exogenous productivity growth slows down over time (and begins at about 1.3%, according to Pizer's estimates). Population growth, which is exogenous, is modelled in a similar manner. Emissions are proportional to BAU-output and endogenous emission reductions. A simple climate module completes the model.

The empirical model encompasses a rich set of different uncertainties, including

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[15] Well-known models in this literature include the DICE-model (Nordhaus (1994)) and the Global 2100 model (Manne and Richels (1992)). For a survey, see e.g. the special issue of Energy Journal, 1999. Nordhaus and Boyer (2000) compares several integrated models, including RICE-99 and DICE-99.

uncertainty utility, cost and technology parameters, as well as parameters describing the development of carbon dioxide in the atmosphere. The econometric model combines data with a prior distribution over the parameters, i.e. Bayesian analysis is used. Data from the national accounts covering the US over the period 1952-1992 are used to estimate structural parameters, such as time preference, productivity growth and capital share. In this way, the marginal distribution of each parameter is obtained, which then provides a coherent way of describing parameter uncertainty.

According to Pizer (1998), the impact of general parameter uncertainty shows most clearly in the long-run; short-run responses are rather similar, whether or not uncertainty is included. He finds that productivity slowdown encourages stricter optimal regulation, thus reversing the Kelly and Kolstad conclusion. The explanation is, according to Pizer, related to how damages are discounted. Slower productivity growth tends to depress interest rates (this follows from the Euler equation). Consequently, if damages are discounted with a lower discount rate, the present value of those damages is higher. Thus, from the point of view of "today" the value of avoiding climate damages in the future gets a relatively higher value.

A puzzling result is that if best-guessed parameter values are imposed, this produces a path with lower welfare, compared to the case when uncertainty is explicitly handled. It appears as if the stricter policy associated with uncertainty case wins more often than it loses, because the gains from avoiding large losses in a bad state of the world, outweigh the cost of overcompliance in the good states. This is related to Weitzman's (1974) price versus quantity result. In Pizer's (1998) model, the marginal benefit curve is relatively flat compared to the marginal cost curve. If follows from Weitzman (1974) that taxes tend to give lower efficiency losses, compared to a quantity instrument, in such settings (see Dasgupta (1982) for a useful discussion of instrument choice under uncertainty)). The proposition that tax instruments are to be preferred in climate policy has some general support, see e.g. Toman (2001).

Finally, we note that the model appears to be rather sensitive to climate parameters. This seems, at least, to be true for the original DICE-model and there are good reasons to believe that this conclusion carries over. An important parameter is the climate sensitivity, which is set to 2.9 degrees Celsius in the standard DICE model. It is allowed to vary in Pizer's model according to a uniform 5-point distribution on the interval (1.5-4.5). Keller et al (2000) illustrate the key role played by this parameter in their analysis of potential thermohaline collapse, within a slightly modified DICE-model.

6.5 Irreversibility, option values and precaution.

There is a group of papers that focus on the modeling of irreversibility and the possibility of an option value, as discussed above. These include Fisher and Narain (2002), Gollier et al. (2000), Kolstad (1996 a,b), Pindyck (2000), Ulph and Ulph

(1997), and several others.[16] We group them together because they have many points in common. In an interesting and provocative paper, Ulph and Ulph focus directly on the question of whether there are option values associated with the preservation of the existing climate system. As already noted, the preconditions necessary for the existence of an option value seem to be satisfied in the context of climate change. We expect to learn about the costs of climate change and about the costs of avoiding it over the next decades. And we expect that some of the decisions that we could take will have consequences that are irreversible. These are the hallmarks of decisions that give rise to option values associated with conservation - the pioneering studies by Arrow and Fisher (1974) and by Henry (1974a,b) have exactly these properties. But although these conditions are necessary for the existence of option values they are not sufficient. Kolstad uses a similar framework and asks a similar question: it is to his paper that we owe the observation that there is another possible real option value at work here. If substantial sunk costs must be incurred to begin the process of abating greenhouse gas emission and avoiding or minimizing climate change, if the return to this investment is the avoidance of climate change, and if we learn about the value of this over time, then there is also a real option value associated with postponing investment in greenhouse gas abatement. So in Kolstad's model, which like the general model above has both GHG accumulation and investment in abatement capital, there are two option values acting in opposition in this framework. Both Ulph and Ulph and Kolstad use a result of Epstein's (1980) which can be applied to the analysis of learning and option values: this is in some sense a generalization of the famous papers by Henry and Arrow and Fisher and gives conditions that are necessary and sufficient for the existence of option values. Ulph and Ulph and Kolstad give conditions under which there are option values associated with the preservation of the existing climate regime, and it is clear that these conditions are quite restrictive - although there is no suggestion that they are necessary. Ulph and Ulph, Kolstad and Fisher and Narain specialize to discrete time two or three period models in order to find solutions. An unattractive feature of the Epstein result, and of some others based on it, is that the third derivative of the utility function is a key variable: an inequality involving this third derivative determines whether or not there is an option value. From a decision-making perspective this is unappealing: we clearly have little or no idea about the sign, let alone the value, of the third derivative, although it has to be recognized that in other problems involving choice under uncertainty the third derivative of the utility function has been a key variable. Fisher and Narain have a more encouraging outcome: in their formulation the index of relative risk aversion is the important parameter. Their paper has a good summary of earlier results in its introduction, and makes an interesting observation about irreversibility of investment in abatement capital: they note that there are two possible interpretations here. One

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[16] See also the early and influential papers by Malinvaud (1969) and Freixas and Laffont (1984), the results of which are incorporated in many of the papers that we review. Another recent paper that we do not review in detail for reasons of space is Torvanger (1997).

is to measure irreversibility by the durability of the capital, as in the Kolstad paper: the other is to define investment in abatement capital as irreversible if that capital is "non-shiftable" in the terminology of optimal growth theorists (Arrow and Kurz (1970)) - i.e. if it cannot be consumed or used in some other sector. Fisher and Narain note that the consequences of irreversibility of abatement investment depend on which of these definitions one uses, and that they are somewhat more intuitive if one uses the conventional optimal growth interpretation of irreversibility. Fisher and Narain also compare results with exogenous and endogenous climate risks - i.e. in the cases where the probability distribution of damages due to greenhouse gas accumulation is affected by the stock of greenhouse gases. The other papers take this distribution to be exogenous.

Pindyck works with the most general of the models in this category, using a multi-period stochastic optimal growth model. Not surprisingly he gives only numerical solutions, and offers a very appropriate summary of the issues and of why it proves difficult to reach firm conclusions about the nature and direction of option values. He comments that "I have focused largely on a one-time policy adoption to reduce emissions of a pollutant. If the policy imposes sunk costs on society, and if it can be delayed, there is an opportunity cost of adopting the policy now rather than waiting for more information. This is analogous to the incentive to wait that arises with irreversible investment decisions. In the case of environmental policy, however, this opportunity cost must be balanced against the opportunity "benefit" of early action - a reduced stock of pollutant that might decay only slowly, imposing irreversible costs on society." He goes on to make comments that are specific to his particular model structure, but are nevertheless enlightening on how things work in this context. "In the simple models presented in this paper, an increase in uncertainty, whether over future costs and benefits of reduced emissions, or over the evolution of the stock of pollutant, leads to a higher threshold for policy adoption. This is because policy adoption involves a sunk cost associated with a discrete reduction in the entire trajectory of future emissions, whereas inaction over any small time interval only involves continued emissions over that interval...... The validity of this result depends on the extent to which environmental policy is indeed irreversible, in the sense of involving commitments to future flows of sunk costs." An interpretation of this seems to be that if policies are flexible and do not necessarily involve commitments to their continuation over long periods, then the asymmetry that he finds would vanish and there would no longer be a tendency of greater uncertainty to favor a more cautious adoption of policies. This in turn suggests that we need to spend more time than we have thinking about the design of policies in this area, and in particular ensuring that they are flexible and permit changes in response to new information.

Gollier et al. (2000) tackle a similar set of questions but from a slightly different perspective. They use the idea of the "precautionary principle" as the organizing theme of their work. They quote the 1992 Rio Declaration (Article 15) as a statement of this: *"where there are threats of serious and irreversible damage, lack of full* *scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."* The reference to scientific uncertainty here implies, for the authors, the possible resolution of this uncertainty by research and learning. Most economists, if asked to think of a justification for this principle, would probably couch it in terms of learning, irreversibilities and option values, so intuitively we think we two are related. Gollier et al note that in fact the precautionary principle can be given a formal justification without invoking irreversibilities, just assuming a stock damage effect and possible learning over time. They consider two economies that are identical except in the way the information structure evolves over time. They then say that the precautionary principle holds if in the economy in which more information becomes available over time we do not invest less in damage prevention: for them the essence of the precautionary principle is a positive relationship between information acquisition and precaution. They note, as in most of the models already discussed, that there are two contradictory effects. One is that we invest less in prevention in the economy which may learn more because this investment may be inefficient: when we know more we may be able to choose better investments. They describe this as the "learn then act" strategy. The opposing tendency is generated by the fact that if we follow this strategy then the risk that society faces in the future will be greater. The principle result of the Gollier et al paper is that the balance between these two effects depends on the shape of the utility function and in particular on whether or not society shows "prudence". Prudence is equivalent to a positive third derivative of the utility function: a prudent person increases her savings in the face of an increase in the risk associated with future revenues (Kimball (1990)). For a class of utility functions Gollier et al. give necessary and sufficient conditions for the precautionary principle to hold, but note that outside of this class there are no general results. They then go on to consider the relationship between the precautionary principle and irreversibility.

In a very interesting paper, Carpenter, Ludwig and Brock (1999) set out a radically different approach. Their paper is not in fact about climate change: the title is "Management of Eutrophication for Lakes Subject to Potentially Irreversible Change." The problem addressed can be summarized as follows. In a farming region, such as the mid West of the USA, phosphorous P is applied as a fertilizer to the land around a lake and some of it runs from there into the lake. In sufficient concentration in the lake, it can cause a change in the biological state of the lake, to a potentially stable state of eutrophication in which the lake is unproductive for most human uses. So eutrophication is irreversible. The response to P concentration is highly non-linear and the concentration of P depends not only on the runoff but also on temperature and rainfall, which are random. How should we manage the runoff of P over time to maximize the expected discounted value of benefits net of the costs of P mitigation? This problem has all the structure of the climate problem: indeed as we said in the first discussion of irreversibilities, the climate system is a complex nonlinear dynamical system that may change regime under human perturbation. This is exactly what

Carpenter, Ludwig and Brock model treats, though for a more finite problem. They talk about the concept of resilience, “the capacity of a non-linear system to remain within a stability domain....” This concept has been widely used in mathematical ecology. They model the dynamics of the interacting lake and agricultural systems as a nonlinear dynamical system with several different locally stable states, one of which is highly unattractive. Avoiding this state is costly, so that there are trade-offs to be made. And the stochasticity of the weather means that the problem has to be seen in probabilistic terms. An interesting conclusion that these authors reach is the following: “An important lesson from this analysis is a precautionary principle. If P inputs are stochastic, lags occur in implementing P input policy, or decision makers are uncertain about lake response to altered P inputs, then P input targets should be reduced. In reality, all of these factors - stochasticity, lags, uncertainty - occur to some degree. Therefore, if maximum economic benefit is the goal of lake management, P input levels should be reduced below levels derived from traditional limnological models. The reduction in P input targets represents the cost a decision maker should be willing to pay as insurance against the risk that the lake will recover slowly or not at all from eutrophication. This general result resembles those derived in the case of harvest policies for living resources subject to catastrophic collapse.” They go on to say that “We believe that the precautionary principle that emerges from our model applies to a wide range of scenarios in which maximum benefit is sought from an ecosystem subject to hysteretic or irreversible changes.”

The model of Carpenter and coauthors seems very readily applicable to climate change: as we have noted above, the climate system may in some respects be irreversible and in some aspects it can be modelled as a dynamical nonlinear system with several basins of attraction - this is the way in which climate modelers represent the alternative states of thermohaline circulation and the Gulf Stream. And even if we are dealing with aspects of the climate system that do not have this characteristic, the changes in ecosystems driven by the climate are very likely to have exactly the characteristics considered by Carpenter, Ludwig and Brock (1999). So considering the climate system and its ecological consequences, which is what is relevant from the social and economic perspective, this seems like a productive framework. In this context the precautionary principle enunciated by Carpenter, Ludwig and Brock (1999) is thought-provoking. Little as clear as this has emerged from the other models cited here. Their result is suggestive of the certainties of the early papers of Arrow-Fisher and Henry. In part this probably reflects the advantages of modelling the system’s dynamics explicitly, and perhaps also reflects the fact that the Carpenter et al. omits - quite legitimately in their context - one issue that is central to the work of Kolstad, Ulph and Ulph and others cited above. This is the need to make a durable investment in greenhouse gas abatement. In controlling the runoff of P there is no equivalent: the application of P can be controlled on a day-to-day basis and can be decreased without prior investments in capital equipment. It would be of great interest to know whether the Carpenter, Ludwig and Brock results would survive the need for investment to control P runoff.

7 Climate change and risk management

Next we discuss the institutional framework with which we could manage the risks arising from climate change. Economists have two standard models of risk-allocation in a market economy. The more general is that of Arrow and Debreu, in which agents trade "contingent commodities". The alternative is the model of insurance via risk-pooling in large populations. Neither can address fully all the particular characteristics of global environmental risks. In particular, both assume the risks to be known in some sense, and to be exogenous.

In the Arrow-Debreu framework there is a set of "states of nature." The probabilities of these being realized are exogenous and these states represent the sources of uncertainty. Classically one thinks of events such as earthquakes and meteor strikes. Their occurrences are assumed to be exogenous to the economic system, and not affected by economic activity. Agents in the economy are allowed to trade commodities contingent on the values of these exogenous variables. These are called "state-contingent commodities". With a complete set of markets for state-contingent commodities, the first theorem of welfare economics holds for economies under uncertainty: an ex-ante Pareto efficient allocation of resources can be attained by a competitive economy with uncertainty about exogenous variables.

Arrow showed that efficiency can in fact be attained by using a mixture of securities markets and markets for non-contingent commodities, so that a complete set of contingent commodity markets is not required. This observation provides a natural and important role for securities markets in the allocation of risk-bearing. The securities used are contracts that pay one unit if and only if a particular state occurs. While the contingent contract approach is in principle all-inclusive and covers most conceivable cases of uncertainty, in practical terms there are cases where it can be impossible to implement. It can be very demanding in terms of the number of markets required. For example, if agents face individual risks (i.e., risks whose probabilities vary from individual to individual), then in a population of 100 similar agents each of whom faces two possible states, the number of markets required would be 2^{100} (see Chichilnisky and Heal (1998)). The number of markets required is so large as to make the contingent contract approach unrealistic.

The use of insurance markets for pooling risks is a less general but more practical alternative. This requires that populations be large and that the risks be small, similar and statistically independent. The law of large numbers then operates and the frequency of occurrence of an insured event in a large sample of agents approximates its frequency in the population as a whole. To be precise, assume that each of N people faces a loss of L with probability π, and an insurance company insures them against this loss. Assume the losses are independent. The loss rate for the population is the expected claims divided by the total insurance offered. A 95%

confidence interval for this is just $\pi \pm \frac{\sqrt{\pi[1-\pi]}}{\sqrt{N}}$ so that the loss rate converges to the actuarial probability as the population increases. There is thus a role for insurance companies to act as intermediaries and pool large numbers of similar but statistically independent risks. In so doing they are able via aggregation and the use of the law of large numbers to neutralize the risks faced by many similar agents. The main references on this are Arrow and Lind (1970) and Malinvaud (1972, 1973).

The insurance approach is at a disadvantage when risks are correlated. When large numbers are likely to be affected at once, risk-pooling will not work. However it does have the advantage relative to the contingent market approach of economizing dramatically on the number of markets needed. In the above example, only two mutual insurance contracts and 2809 securities would be needed instead of 2^{100} contingent contracts.

7.1 Unknown risks

When risks are allocated by trading state-contingent commodities securities, or by risk-pooling and insurance, *it is very important that agents know, or believe that they know, the relative frequencies of the states of nature, at least approximately.* This is obvious when trading insurance contracts. The actuarial calculations needed to set insurance premia can only be performed if the parties believe that the relative frequencies of the insured events are approximately known.

In the Arrow-Debreu approach, it suffices to think of agents maximizing expected utility to appreciate the need for them to know, or at least behave as if they know, the relative frequencies of exogenous states. These frequencies are the weights placed on their utilities from state-dependent consumption. The point is simple: if agents can not assign relative frequencies then their preferences are not well-defined and they cannot act to maximize expected utility.

As we have noted above, in the context of such risks as climate change, ozone depletion and in particular biodiversity loss this is probably much too demanding. Agents, even experts, do not know the frequencies of different states, and recognize that they do not know them. The reviews by Roughgarden and Schneider (1999) and the IPCC TAR of expert judgements on the impact of climate changes emphasizes this. They recognize that there are several different opinions about what these are, but feel unable to choose definitively between these alternatives. In such a case, it is natural to think of the frequency distribution over environmental changes as a state of the world, a risk, in the Savage sense: we do not know what value it will assume, and whatever value this is, it affects economic activity. Ignorance then assumes the role of a collective risk, and can be treated by the use of state-contingent markets.

Chichilnisky and Heal (1993, 1998) formalize this type of situation in a simple general equilibrium model. Each agent faces the risk of being in one of several states (e.g. healthy or sick, productive or unproductive, environmentally impoverished or not, etc.). No-one knows what will be the true frequency distribution of affected agents. A probability is assigned to each of several frequency distributions thought to be possible. A typical probability distribution of this type might state for example that there is a 10% chance that 90% of the population will be harmed by global warming, a 25% chance that 50% of the population will be harmed, etc. The probability distribution over alternative frequency distributions may be different from individual to individual. Again this is consistent with the expert opinions on climate change summarized by Roughgarden and Schneider.

In this framework, we have two levels of uncertainty. The first level of uncertainty is collective: what is the distribution of agents who are harmed in the economy? Will 90% be harmed, or only 30%? This is a question about the aggregate incidence of the phenomenon over the population as a whole. This risk represents or arises from our lack of knowledge of the phenomena at stake.

The second level of uncertainty is individual: it is uncertainty about whether a given agent is harmed or not by climate change. It devolves about questions such as: given that 90% of the population will be harmed or environmentally impoverished, will a particular agent be harmed or not? The issue here is: contingent on a particular overall incidence of the phenomenon, who are the agents who will be affected?

Chichilnisky and Heal (1998) suggests an institutional structure which uses two types of financial instruments which are tailored to these two aspects of the problem. These can lead to efficient allocation in the face of such risks. One instrument is a mutual insurance contract to deal with the risks faced by agents or communities contingent on each possible distribution of harmful effects worldwide. A mutual insurance contract is an agreement between parties subject to similar risks that those who are harmed will be compensated by the others. Examples are agricultural cooperatives of the type recorded in Europe at least since the fifteenth century, and the nineteenth century U.K. workers' associations and friendly societies. These involved agreements between a group of workers that if one were sick and unable to work, he or she would be compensated by the others. In the present context, one could think of groups of communities subject to the possible impact of climate change, with those unharmed compensating the others. Making the terms of such a mutual insurance contract contingent on the distribution of harmful effects worldwide means that there is a different compensation agreement between the parties for each possible aggregate distribution of harmful effects. To know what compensation is due in any particular case, the parties have first to assess the distribution of harmful effects globally, and on the basis of this decide which mutual insurance contract to apply.

Having dealt with individual risks by mutual insurance, we still face collective risks. We need statistical securities to deal with these collective risk induced by uncertainty about the overall distribution of adverse effects. Arrow securities are defined as securities that pay one dollar if and only if a particular state of the world occurs. Statistical securities pay one dollar if and only if there is a particular frequency of affected parties in the population, i.e., if and only if there is a particular statistical state, a state of the economy with specified statistical characteristics. As already noted, the incidence of impacts on the population as a whole is being treated as a "state of the world" in the Arrow-Debreu sense. We treat each possible distribution of adverse affects as a distinct collective state (called a statistical state), and use securities markets to enable parties to transfer wealth between these states. One statistical security is needed for each possible distribution of adverse effects worldwide, because to attain Pareto efficiency each separate state must be covered by a security. The core of the results in Chichilnisky and Heal is that with unknown risks we can trade securities contingent on statistical states and this can allow the uncertainty introduced by alternative probability distributions to be fully hedged.

There are two features of the results which are of general interest. One is the development of a framework for achieving efficient allocations in the face of uncertain individual risks. Given rapid changes in technology with potentially far-reaching environmental impacts and health effects, the problem of providing insurance against such risks is particularly important. It is a matter of very active concern in the insurance industry. The second interesting feature is the way a combination of securities markets and insurance markets can be used to provide a relatively simple institutional structure for dealing with unknowable risks. Current trends in the securitization of certain risks are consistent with this analysis. In Chichilnisky and Heal (1998) it is shown that under certain simplifying assumptions this framework will lead to an efficient allocation of risks in a competitive general equilibrium model. Subsequently Klimpel and Requate (2000) generalized these results.

Another radically different approach to the fact that risks are unknown has been explored by Henry and Henry (2000). A central feature of their analysis is an explicit recognition that we do not have a complete probability distribution over possible climate change events and consequences. There may be changes and consequences that we have not yet envisaged. In such a case the probabilities that we assign to the events about which we do have information must sum to less than one, to leave room for the unknown events. So what we have to work with is a measure on the set of known possible events, whose integral is less than one. And even on the events about which we know something, it is possible that our beliefs can not be described by a measure that satisfies the conditions that are needed for it to be a part of a probability distribution: they may be too imprecise for this. Implementing these observations, which seem quite compelling in the climate change context, requires that we work within the framework of non-additive probabilities on the state space. The prerequisites for following such arguments in detail are more demanding than those for most of the literature that we have reviewed, so we will merely mention this approach, which to us looks particularly promising, and note that it provides another context in which one can formalize a precautionary principle. Precautionary behavior is now motivated in part by the possibility of events and outcomes that we cannot characterize. One is reminded of Hamlet's thoughts on death:

> The dread of something after death
> That undiscovered country from whose bourn

No traveller returns, puzzles the will
And makes us rather bear those ills we have
Than fly to others that we know not of.

Shakespeare seems to have anticipated the precautionary principle here.

7.2 Endogenous risks

The risks we face in environmental change are not only not well known: they are also not exogenous. Almost by definition, they are endogenous and are determined by our behavior. In effect we both create states of nature and determine the probability distributions over these. By creating the states of nature we mean that human actions make possible states of the planetary systems that would not otherwise occur. For example, human actions are leading to patterns of land use and of species diversity that certainly would not have occurred without our actions: intensive agriculture is a form of land use that would not have arisen without human activity, and the transportation of exotic species, a major threat to biodiversity, is also uniquely a product of the patterns of human activity.

In all of the classical models of risk management discussed above, it is assumed that the risks faced are exogenous: that is, they are not affected by human actions. At the microeconomic level, the fact that human actors can affect the probabilities of the risks that they face has long been recognized as a serious problem for the operation of insurance markets, under the title of moral hazard. The focus in this literature has been on the fact that offering insurance to a person may lead her to behave in a way that alters the risk that she faces. Deductibles and co-insurance have been the recommended solutions to the problems that this creates for attaining an efficient allocation of the risks - although they do not lead to a first best outcome.

More recently there has been a literature on endogenous uncertainty in a general equilibrium context.[17] This literature has addressed the issues that arise when agents are uncertain about the values of endogenous variables. A good example is provided by uncertainty about the values of stock prices or of exchange rates. The natural question is whether we can use the device of trading state-contingent contracts to handle this uncertainty. In this case the contracts would have to be contingent on the prices about which agents are uncertain. These have been termed price contingent contracts, or PCSs. It is possible to construct an institutional framework within which trading price-contingent contracts will lead to a fully efficient insurance of the risks associated with uncertainty about prices, and this leads quite naturally to a general equilibrium theory of the role and pricing of derivative securities. The framework involves trading securities contingent on the prices that are realized at equilibrium in a market for PCSs that operates before the market for goods and services opens.

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[17] For dynamic general equilibrium models that includes endogenous probability for climatic catastrophes, including cost-benefit rules, see e.g. Backlund et al (2000).

Heal (1995) considers an exchange economy augmented by the possibility of trading price contingent securities which pay a specified sum if and only if the equilibrium price vector assumes a specified value. Prices play the role played by "states of nature" in the Savage framework, so the determination of the state is endogenous. Agents have expectations about possible prices, and trade price contingent securities to insure price risks. They use these securities to exchange income in price states in which they are well off for income in states in which they are badly off. Before an equilibrium price emerges agents trade these securities, shifting income across price states. This changes their endowments in the exchange economy, which now become price contingent.

How does this relate to the endogeneity of environmental uncertainty? The similarity is that the possible environmental states and their probabilities are determined by human actions, indeed in part by the equilibrium of our economic system and the environmental impacts of the selected activities. The analogy with endogenous price uncertainty suggests an approach based on trading securities contingent on the environmental states before these are realized. This would involve markets on which we trade securities that pay dependent on the amount of climate change and its location and timing, or on the state of the ozone layer in a given year, or on the state of biodiversity. So we would have markets for climate bonds, or ozone bonds or biodiversity bonds. In case this sounds exotic, note that Wall Street already trades hurricane bonds, earthquake bonds, catastrophe futures, Act-of-God bonds and a few others. All of these exist for the purpose of shifting the risks associated with environmental phenomena.

How would such instruments work and what would they contribute? The payoffs from these bonds would shift endowments around in a way that depended on the state of the environment, making the distribution of endowments in the rest of the economic system contingent on the state of the environment, just as PCSs make the distribution of endowments contingent on the vector of equilibrium prices in a general equilibrium model with price uncertainty. Given a state of the environment and a distribution of endowments resulting from environment-contingent bonds, trade would then occur as normal and would lead under the right conditions to an efficient allocation of resources.

By following the arguments in Heal (1995), we can show that this system has a competitive equilibrium at which all agents are insured to precisely the degree that they want against the risks associated with not knowing what the states of the environment and economy will be. The markets for securities contingent on the state of the environment and the economy will provide an efficient allocation of the risks arising from environmental uncertainty. The kinds of markets we have in mind here are exemplified by markets in which one can insure against a certain level of climate change and its economic consequences, captured in the model by the environmental state e and the price vector p. Such markets do not currently exist, but markets for securities continent on the state of the environment do exist, in the form of hurricane bonds and weather swaps. There is currently a proposal to introduce a tradable index of the state of the ENSO (El Nino-Southern Oscillator) cycle, which would be a move closer to a general security whose payoff depends on the state of the climate system. Note that although these markets would allocate efficiently the risks of environmental change, they would not lead to a Pareto efficient allocation, as the externalities associated with behavior that affects the climate are not corrected. That would require a separate set of policy instruments, such as the classical corrective taxes and subsidies or the use of tradable permits. In the formal model presented above, there is no explicit connection between the acts of any one agent and the probabilities of the states $e \in E$, so that these externalities are not addressed. However, if corrective taxes or equivalents (such as permit markets) were in place, then the outcome of these markets would be a Pareto efficient allocation.

8 Conclusion

Climate change involves uncertainties in a breathtaking number of dimensions, including, but not limited to, the fields of natural science and economics. This paper tries to show why economic analysis that explicitly incorporates uncertainty gives some valuable insights into the policy issues raised by the possibility of climate change. True, even if the underlying problems were deterministic, then the economics of this issue would pose many interesting challenges, but formal analysis of decision making under uncertainty must certainly play a dominant role in any economic discussion about climate change policy.

A first point that we make may seem self-serving to non-economists, yet its importance is often overlooked in a discussion that gravitates too much towards the scientific uncertainties. Both empirical and theoretical studies show that we should worry not only about disentangling nature's true blueprint but also about uncertainties that are intrinsic to the economic system, such as discount rates, growth rates and the rate of technological advance. After all, the engine of growth is a driver of climate change and understanding the relevant parts of the economic system should help us make better predictions. Our survey of some of the relevant empirical evidence does bring this point home rather forcefully.

There is a significant economic literature on irreversibilities, option values and the value of flexibility, and this literature plays a dominant role in our discussions. A key insight from this literature is that option values have two dimensions: there is a value of waiting for more information in order not to destroy irreversibly some natural process, but there is also a value of waiting to invest scarce resources in abatement technology. While the relevant empirical evidence on option values is scarce, to say the least, economic theory gives some useful leads on where to look further and why one needs to strike a balance between countervailing forces.

To this we must add the sobering fact that there are future unknown risks that will require scarce economic resources. Somehow we need to find a balance between allocating resources to risks that are known today and to future unknown risks. As Wildawsky (1988, p. 217) eloquently put it “Insofar as we today should consider the welfare of future generations, our duty lies not in leaving them exactly the social and environmental life we think they ought to have, but rather in making it possible for them to inherit a climate of open choices. That is, in leaving behind a larger level of general fluid resources to be redirected as they, not we, see fit.” Climate policy that properly takes into account the value of flexibility and adaptation seems to be the most promising way of satisfying this recommendation.

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