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Costs of Adjustment to Climate Change

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Costs of adjustment to climate change

There is considerable scientific evidence to suggest that human activity will lead to significant climatic change over the next fifty years. The most important example is the ‘greenhouse effect’ which, it has been predicted, will lead to an increase in global mean temperature of between 0.5°C and 2.5°C over the next 50 years and between 1.4°C and 5.8℃ over the next 100 years (Intergovernmental Panel on Climate Change 2001). It is also predicted that sea levels will rise by between 0.09 and 0.88 metres over the next 100 years.

In response to these predictions a large number of developed countries signed the Kyoto protocol in 1997. The Protocol is aimed at mitigating global warming, primarily by reducing net emissions of the main ‘greenhouse gases’: carbon dioxide (CO2), carbon monoxide (CO), nitrous oxide (NO) methane (CH4) and chlorofluorocarbons (CFCs)). A variety of proposals have been put forward aimed at achieving the reductions in emissions proposed under the Protocol.

Some of these proposals, most notably reductions in CFC emissions, involve relatively low costs and have additional benefits, such as reduced damage to the atmospheric ozone layer, sufficient to justify them even in the absence of concerns about global warming. Others, such as reductions in emissions sufficient to stabilize the current atmospheric stocks of CO2, would involve substantial economic and social costs.

The government of the United States has announced its intention not to ratify or implement the Kyoto Protocol. In part, this reflects the view of a number of economists and others that the costs of global warming are less than the costs of any action to reduce greenhouse emissions (Moore 1998).

In order to assess the validity of such claims, it is necessary to formulate some estimates of the likely costs of climatic change. One approach is to catalog likely adverse effects such as the submersion of some Pacific islands, increased severity of monsoons and hurricanes in tropical and sub-tropical areas, higher airconditioning costs, increased prevalence of tropical diseases and reduced agricultural yields or, at an extreme,_the conversion of currently fertile areas into desert (IIntergovernmental Panel on Climate Change 2001). However, critics have argued that such an estimate would be incomplete because of the failure to take into account offsetting benefits. To take the simplest example, cool areas with short growing seasons could see an increase in agricultural yields. Hence, critics argue is not clear whether worldwide growing conditions would improve or deteriorate.

After seeking to take account of both costs and benefits, economists such as Nordhaus (1991), Schelling (1991, 1992) and Mendelsohn, Nordhaus, and Shaw (1994), have produced estimates suggesting that the net costs of climatic change will be quite small, at least for developed countries such as the United States, and that climate change may even be beneficial. Nordhaus estimates the quantifiable net damages at 0.26 per cent of GNP. Schelling comes to the same conclusion as far as the presently developed countries are concerned. He suggests however, that impacts on less developed countries may be substantial. Mendelsohn, Nordhaus, and Shaw (1994) estimate that a 5° F increase in mean temperatures will yield changes in US farmland rents ranging from a 4.9 per cent loss to a 1.2 per cent gain.

As Quiggin and Horowitz (1999) observe, estimates of this kind may be interpreted using the concept of a climatic optimum. For a typical specification of agricultural technology, as employed in these models, there exists an optimal configuration of seasonal temperatures and rainfall. Climate change will be costly (or beneficial) if, on average, climatic conditions in the area modelled move further away from (or closer to) the climatic optimum. Cool areas are ones that are below their climatic optimum. They benefit from an increase in average temperature. Areas that are already hot are above their climatic optimum and will suffer from an average temperature increase.

Quiggin and Horowitz (1999) show that the model of Mendelsohn, Nordhaus, and Shaw (1994) is not well-behaved, in that the optimal values for climatic variables are either implausible (an optimal July temperature of -68°F) or non-existent, because the returns function is not concave. Hence, although the equations estimated by Mendelsohn, Nordhaus, and Shaw (1994) fit the data reasonably well, they will not, in general, be well-behaved for data points lying outside the range of the data set used in estimation. Similar criticisms are made by Darwin (1999). Responding, Mendelsohn, Nordhaus, and Shaw (1999) state that revised versions of the model display the necessary concavity properties for the existence of a well-behaved optimum.

Several questions arise from consideration of the concept of a climatic optimum. If such an optimum exists, what are its characteristics? Are agricultural areas in general above or below this optimum? Does the concept of a climatic optimum adequately capture the potential effects of climate change? The primary focus of this paper will be on the last of these questions.

In particular, the primary object of this paper is to consider issues arising in estimation of the cost of adjusting to climate change. The central result is that climate change will reduce welfare whenever the rate of adjustment required to adapt capital stocks (interpreted broadly to indlue natural resource stocks) to changing climate is more rapid than the 'natural' rate of adjustment associated with market processes. Furthermore, this welfare loss is unrelated to how close lands are to their climatic optimum. The costs of climate change can be large even when lands are close to their climatic optimum, or evenly distributed both above and below that optimum.

This distinction is important because when land is distributed both above and below the optimum, the static costs of climate change will appear small. The dynamic costs will, in general, be large. Estimates of climate change based on the climatic optimum will therefore miss an important cost category.

The paper is organized as follows. First, we consider issues associated with the identification of a globally optimal climate and the implications for estimates of the costs and benefits of global warming. Second, we consider the formal properties of a dynamic model and the associated estimates of adjustment costs. Third, we consisder issues relating to uncertainty and variability. Finally, a preliminary attempt is made to quantify some of the sources of loss associated with global climatic change in a dynamic framework. Particular attention is paid to capital stocks associated with agriculture and to natural resources.

The Optimal Climate Approach

The notion of an optimal climate is implicit in many studies of the costs and benefits of global warming. However, different procedures for estimating the optimum yield different outcomes. Comparisons of income per person generally support the view that a temperate climate similar to that of Northern Europe is optimal

Horowitz (2001) argued that one way of gauging how global warming will affect an economy is to look at the economic performance of countries that are warmer. He examined the income-temperature relationship for a cross-section of 156 countries in 1999. After separating OECD countries and accounting for historical factors (which would not be affected by temperature change), he concluded 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. It is worth noting that if climate change delays the transition from a non-OECD to an OECD-type economy, the costs of climate change would be much larger. Using similar methods but not correcting for historical factors or OECD membership, Choiniere and Horowitz estimate the income-temperature gradient in log-log form to be -3.42

On the other hand, consideration of current agricultural technology gives rise to rather different results. Early studies modelled the effects of climate change on crop yields, under the assumption that existing patterns of land use would remain unchanged.

This procedure does not involve the assumption of a unique climatic optimum, since the optimum will, in general, be different for every land use.

Mendelsohn, Nordhaus, and Shaw (1994) criticized the latter approach as a 'dumb farmer' model since it assumed that farmers would not adjust their land use in response to climate change. Mendelsohn, Nordhaus, and Shaw observed that land rents provide a measure of the value of land in its most valuable use, and considered the impact of climate on land rent. Under standard assumptions, discussed below, this procedure involves the assumption of a unique optimal climate. A similar implicit assumption is central to the analysis of Nordhaus (1991) and Schelling (1991, 1992) and is carried over into critical responses such as those of Cline (1991).

To consider the global optimum approach in more detail it is useful to introduce some formal notation. The value of production in land area i is given by a function $V_i(T_i)$ where T_i is an index of the climate in region i (which may be taken, in the simplest case, to be summarized by mean temperature). The function V_i is assumed to be concave in T_i with a maximum at some T_i* . Let I^+ denote the set of regions for which $T_i > T_i*$ and I^- denote the set of regions for which $T_i > T*$.

Now consider a small change in climate such that, in each region, the climate index increases to $T_i+\delta_i$. For simplicity, we assume that $\delta_i > 0$ i.

The impact on agricultural value is given by

$$\Delta V= \Sigma_- \{V_i(T_i+\delta_i) - V_i(T_i)\} - \Sigma_+\{V_i(T_i)-V_i(T_i+\delta_i)\}$$

where Σ_- denotes the sum of gains taken over the regions in I,$^-$ and Σ_+ denotes the sum of losses taken over the regions in I^+. Both sums are positive. Thus the net effect ΔV is the difference between the benefits accruing to areas that are initially colder than the optimum and the gains accruing to areas that are initially warmer than the optimum.

Assuming that $T*$ is associated with a moderate (say, warm temperate) climate, and that L is a symmetric function, the net effect ΔV of global warming is a residual which will be small in relation either to the gains in I^- or the losses in I^+. Hence, estimates derived in this way will inevitably be small in relation to total agricultural output.

To illustrate this point, consider the case when the elements of T are evenly spaced, that is $T_{i+1} = T_i + \Delta$, I, and the temperature-value relationship is the same in all regions, and is given by a function $V(T_i)$. Then the effect on $\boldsymbol{T}$ of a uniform increase in all temperatures by Δ may be obtained by deleting T^1 and replacing T^m with $T^m + \Delta$. By the concavity of L, the contribution of climate to production will be least for the extreme values of I and greatest for the intermediate values. Hence, the change in V, given by $V(T^m + \Delta)\text{-}V(T_1)$ must be small. The sign of the estimate may be either positive or negative, and will be sensitive to small changes in modelling assumptions.

Because ΔV is a residual, estimates of its sign will be sensitive to variations in modeling assumptions. For example, a conclusion that the impact of warming is negative could be reversed either by an upward revision of the estimated optimal temperature T^* or by changes in detailed estimates of the pattern of warming, leading to more warming at higher latitudes and less warming at lower latitudes.

This reasoning is not affected by uncertainty. Suppose that there is uncertainty about the values of T^* and δ. Taking expectations with respect to a linear approximation to V, the expression ΔV derived above is still an unbiased estimate of the net impact of warming, assuming that the underlying model is valid. Observe that, since $\Delta V/\Delta T_i$ is positive in some regions, negative in others, and close to zero on average the linearized estimate will be unbiased.

Similarly, it does not matter that the change in temperature is unlikely to be uniform. Some areas will have a greater than average increase in mean temperature, others a lower than average increase, or even a decrease. Provided there is no systematic pattern to this variation, the argument presented here remains valid. The only important possibility is that global warming might act to increase (or decrease) the variation in the distribution of temperatures as would occur if warming is greatest (least) at the Equator, and least (greatest) in high latitudes.

The type of shift that is likely to occur in the new equilibrium may be estimated using the following back-of-the-envelope approach. From the isotherms observed under the existing temperature distribution, a rise in mean annual temperature of about 3° *C* is associated with a move of about 4.5 degrees of latitude or 500 km[1] towards the equator. Conversely, if global mean temperatures were to rise by a uniform 3°, climates would migrate towards the poles, on average by about 500km. The exception is that the extremely cold climate currently prevailing at the poles would disappear and that a new high temperature climate would prevail at the equator.

The Dynamic Approach

To understand the dynamic aspects of the problem, it is necessary to model the production technology in more detail. Assume an aggregate capital stock K and labor force N. There are m regions. In each region, two classes of productive activity may be undertaken. The first class of activity is independent of climate and yields an output $f(K_{i1}, N_{i1})$ in region i, where K_{i1} and N_{i1} are the capital and labor used in region i for the first class of activities. The second class consists of activities that are dependent on climate. Their output is $g(K_{i2}, N_{i2}, L_i(T_i))$,. where K_{i2}, N_{i2} are the capital and labor used in region i for activities in the second class.

Total output produced in region i is given by

(1) $$V_i = f(K_{i1}, N_{i1}) + g(K_{i2}, N_{i2}, L_i(T_i))$$

Note that all differences between regions are assumed to be captured by L_i so the functions f,g are the same for all regions.

Under either optimal planning or a competitive equilibrium there exists a set of

[1] In calculations of this kind, the fact that the metric system is based on the earth's circumference makes the back-of-the-envelope approach easy. The arc from equator to pole is 10 000 km, so that 1 degree of latitude = 111 km.

capital and labor allocations K^*, N^* such that $V = \Sigma_i V_i$ is maximized subject to the constraints $K_{i1} + K_{i2} = K$, $N_{i1} + N_{i2} = N_i$.

The value of this optimal outcome depends on the distribution of temperature. It also depends on the aggregate factor endowments but these will be treated as fixed.

(2) $$V = \phi(L_1, L_2 \dots L_m) = \phi(T_1, T_2 \dots T_m) = max_{K^*, L^*} \quad Yi.$$

If all of the regions 1, 2 ... m are identical (except for differences in climate) then V will depend only on the set $\boldsymbol{T} = \{T_i: i \in 1, 2 \dots m\}$.

Suppose that the time path of climate T_{it} is known in advance for all i, t. The planning problem is to maximize an objective of the form

(3) $$V = \Sigma_t e^{-rt} Y_{it}$$

subject to constraints on capital stock adjustment described below. We shall denote the initial distribution of temperature by T_{i0} i= 1...n., and the initial stocks of capital and labor by K_{ij0}, i= 1...n, j=1..m and N_{i0} i= 1...n. It will be assumed that the system is initially in equilibrium.

We now suppose that temperature increases by a constant amount δ per period. Thus, a comparative static analysis could be undertaken by fixing some time interval τ (for example, the doubling time of global CO_2 stocks) and undertaking the analysis of the previous section with $\Delta = \delta\tau$. As we have seen, for moderate values of Δ, a zero net impact is derived.

Instead, we now turn to a dynamic analysis of the effects of a change in climate. The crucial feature of the dynamic approach is the treatment of capital stocks. In the static approaches, the capital stock is homogenous, both in form and in its allocation across regions. In the dynamic approach, capital is heterogeneous and location-specific. The basic approach is that of the 'putty-clay' model. Divergences in the marginal product of capital, arising in the present context from climatic change, call forth adjustment in the form of new investment in areas where the marginal product is high. In areas where the marginal product is low, the capital stock declines as a result of depreciation or, in extreme cases, scrappage. To provide a simple comparison with the optimal climate approach, it will be useful to consider first the case when total capital stock is constant (new investment = depreciation in every period).

The production technology for region i is given by

(4) $$V_{it} = f(K_{i1t}, N_{i1t}) + g(K_{i2t}, K_{i3t}, \ldots K_{imt}, N_{i2t}, \ldots N_{imt}, L_i(T_{it}))$$

where K_{ijt} represents the stock of the j-th type of capital in region i at time t. As in the optimal climate model, K_{i1t} represents the capital stock associated with activities that are independent of climate. The capital stock associated with climate-dependent activities has been disaggregated into stocks of (m-1) specific classes of capital. A similar disaggregation has been undertaken for labor.

Capital stocks evolve subject to the constraints that

(5) $$\Sigma_i \Sigma_j K_{ijt} = K \quad t$$

and

(6) $$K_{ijt} \geq (1- \gamma_{ij})\, K_{ij(t-1)}$$

where

γ_{ij} is the rate of depreciation for the j-th type of capital in region i.

Denote by ***K***,***N*** the time paths of the regional allocations of capital and labor and let

(7) $$V^*(\delta) = Max_{\boldsymbol{K},\boldsymbol{N}}\ V(\boldsymbol{K},\boldsymbol{N},\boldsymbol{T}(\delta))$$

where V is defined as in (3) and ***K*** satisfies the constraints (6). Our key result is

Proposition 1: Suppose $\Delta V=0$. Then V^* is a concave function of δ with maximum at $\delta=0$.

Proof: By the initial equilibrium assumption, the optimal path when $\delta=0$ has $K_{ijt} = K_{ij0}$ i, j, t. Define the unconstrained optimal path for arbitrary δ by $\boldsymbol{K}^{**}(\delta)$, and the associated return by $V^{**}(\delta)$. Then $V^{**}(\delta) \geq V^{*}(\delta)$. This inequality will be strict whenever any of the constraints (6) is binding. By Proposition 1, $V^{*}(0) = V^{**}(\delta)$, so V^{*} takes its maximum at zero. Concavity follows from the properties of the production function.

It follows that ΔV the estimate of loss derived in the previous section is, in fact, a lower bound. Under certainty the lower bound will be attained if and only if all of the required capital stock adjustments are consistent with the constraint (5). That is, in any region i where the stock of capital j is required to contract as T changes, the rate of adjustment needed to maintain optimality must be less than γ_{ij}.

Adjustment costs

From the discussion above, costs of adjustment to climatic change will arise if capital stocks

(i) are dependent on climate for their optimal location; and

(ii) depreciate more slowly than is required to permit easy adjustment to changing climate.

Two main categories of capital stock might satisfy these conditions. The first is that of long-lasting 'infrastructure' investments, such as harbors, dams and irrigation systems and grain handling facilities.

Consider first the example of grain handling. Suppose that climatic change over the next fifty years results in an increase of 2.5° C in mean global temperature. As shown above, this increase has the effect of shifting the zone of grain production 500 km further from the Equator. In the optimal climate approach, the impact would depend on the area of potentially arable land at different latitudes.

A dynamic estimate yields different results. Assuming, for the moment, a uniform rate of warming yielding a 2.5° C increase over 50 years, the annual change of 0.05° C per year implies a shift of 10 km per year in the zone of wheat production. Although his shift appears small, it is large enough to imply significant capital losses in grain handling.

Fisher and Quiggin (1988) estimate the optimal service radius for Australian grain handling facilities at 25 km. Hence facilities initially at the margin of the wheat production zone will be sub-optimally located after 3 years of warming at a rate of 0.05° per year. By contrast, the normal service life of vertical and horizontal storage facilities is several decades. In areas currently close to the margin, this implies a capital loss, as grain production ceases before the facilities end their useful life. In areas currently well away from the margin, but within the 500km range, it is likely that existing facilities will require replacement before grain production ceases. Since it would be uneconomic to replace long-lived storage facilities, it will be necessary to resort to methods such as bunker storage with lower capital costs and higher operating costs. Thus, the process of global warming will impose continuing costs.

A similar analysis applies to harbors, beachfront houses, and other capital goods whose value is derived from a seafront location. In this case, the central variable is the rate of rise of sea levels.

Assume that the rate of sea level rise is 1 cm /year (implying a 1-meter rise over 100 years) and that this implies an inward shift in the natural coastline of 5 meters/year. In relation to existing capital stocks, three options are available. First, they may be modified to cope with higher sea levels. Second, they may be dismantled and moved inward. Third, they may be abandoned.

Once again, there are continuing losses over and above those associated with the existing capital stocks. New capital investments must be modified to take account of shorter lifetimes and higher maintenance costs. Consider the example of beachfront housing. If we interpret the beachfront as the area within, say, 50 meters of the high water-mark, a beachfront house will have a natural life of 10 years. After this, it must be built up, at steadily increasing cost, or abandoned. This dilemma is already being faced in areas of the coastal United States with naturally shifting shorelines .

In both of the cases described above, damages are related fairly directly to the rate of change. As shown in Proposition 2, the damage will be a convex, rather than a linear, function of the rate of warming. Nevertheless, it should be relatively straightforward, having derived cost estimates for some predicted mean rate of warming, to adjust those estimates to take account of new information or more detailed regional forecasts.

Rather different problems arise when we consider facilities such as dams, irrigation systems and hydro-electric power generation. The value of these facilities depends on a number of climatic factors including precipitation in the catchment areas, evaporation rates and the suitability of the irrigated areas for growing different crops. All of these will be affected by climatic change. Most of the relevant effects are unpredictable on the basis of present knowledge . The only thing that can be predicted with certainty is that the optimal location of these systems will change and that this change will be costly.

The distinction between the dynamic approach and the optimal climate approach is particularly clear in the case of dams. The evidence available at present gives no grounds for supposing that the distribution of rainfall and hydrological systems resulting from global climatic change will be any more or less suitable for irrigation or hydro-electricity than the present distribution. Hence an optimal climate analysis must yield a net cost estimate of zero.

From the dynamic perspective the critical point in favor of the current rainfall distributions is that our existing infrastructure is designed to exploit it. Either an increase or a decrease in rainfall in the catchment area for an existing dam will impose losses if the change is sufficiently large. A decrease in rainfall will reduce the economic value of the services provided by the dam. An increase in rainfall increases the severity of the flood events (conventionally measured by 50 and 100 year floods) the dam must withstand. This creates the possibility that the dam will require costly modifications or even replacement if safety standards are to be maintained.

Natural capital

The second main category is that of 'natural capital' including forests and ecosystems valued for tourism, or in their own right. Forests valued primarily for the production of one or a few timber species may be treated in much the same manner as human-made capital. The main difference is that the adjustment mechanism cannot be represented in terms of exponential decay taking place at a constant rate. Rather, adjustment occurs when trees are felled in one area and replaced in another. Typical rotation periods in plantation forestry range from 20 to 40 years. In order for production of a given species to be feasible in a given area, it is necessary that the climate in that area should, throughout the rotation period, be consistent with the survival and growth of the species in question. Global warming implies that, on average, the zone in which climate is suitable will move northward by about 500 km during this period . Hence, many existing forests with limited capacity for adaptation to climatic change will suffer tree decline and dieback. A further implication is that reafforestation will be constrained by the need to choose replacement species, such as the Ponderosa pine, that are capable of flourishing in a wide range of climatic conditions.

The US Environmental Protection Authority (1989) estimates that the loss in healthy woodland area in the United States could be made up by a reafforestation program costing about $US0.5 billion per year. It is not clear whether this estimate includes the capital losses associated with the dieback of existing forests. Also, if forests suffering dieback are not cleared, there is an increase in the land devoted to forestry with no corresponding increase in output. The opportunity cost of this land needs to be taken into account.

It is likely that losses in timber production would represent only a small part of the social loss associated with large-scale dieback. Losses in recreation values arise from dieback in existing forests and their replacement by monocultures of highly adaptable species. These losses could be estimated using hedonic pricing and travel cost methods (McConnell and Bockstael 1979). Deeper social concerns about large-scale forest decline are more difficult to quantify. However, forest decline resulting from acid rain has been a major social concern in both Europe and North America. The argument presented here suggests that the negative effects of global climatic change on forests will be comparable to those of acid rain.

Whole ecosystems require a different treatment within the dynamic framework. In place of the notion of depreciation, it is natural to think in terms of the rate of ecological succession arising in response to a disturbance in the environment. If the process of succession is more rapid than the rate of climatic change, ecosystems will migrate away from the Equator as temperatures rise, and the overall distribution will be essentially stable. However, if the process of succession is insufficiently rapid at a given point, the ecosystem will be in an unstable state. Some species will become extinct and others will multiply to pest proportions. Many of the ecological succession processes that have been observed proceed at rates of meters per year, rather than the kilometers per year required for adjustment to anticipated global warming.

A closely related point may be made by comparing the time scale of global warming with previous examples of climatic change, for which some evidence on the pattern of ecological adjustment is available. The anticipated rate of increase in mean temperatures is considerably more rapid that any which has occurred as a result of natural climatic processes. Hence there is no reason to expect that the mechanisms of ecological succession developed as a result of previous evolutionary pressure will be sufficiently flexible to permit adjustment to these changes.

As in the case of forests, large-scale extinctions will involve economic losses associated with declining recreational values, loss of scientific value, loss of potentially useful species and so forth. It seems clear, however, that this list of economic losses comes nowhere near capturing the concerns of many citizens about the impact of large-scale extinction. The way in which concerns not associated with consumption of goods or services should be incorporated into economic analysis has been the subject of considerable controversy recently. One approach is based on the notion of existence value (Krutilla 1964). Since, for most people, no market transactions are associated with the preservation or extinction of species, existence values must be assessed using direct questioning methods such as the contingent valuation method (Mitchell and Carson 1989). This approach has been criticized on various grounds (Kahneman and Knetsch, Nelson and Rosenthal, Quiggin).

An alternative approach may be used to obtain a fairly robust lower bound. It seems reasonable to conclude that the rates of ecological loss associated with global climatic change at the rates estimated on the basis of median predictions of global warming will be greater than those prevailing in the developed countries prior to the passage of the extensive environmental legislation of the 1960s and 1970s. It has been estimated (Denison 1979a, 1979b) for the US that over the period 1975 to 1978 the cumulative impact of this legislation was to reduce measured GNP by 0.6 per cent. Extrapolation over the period 1970-90 suggests a cumulative impact of around 2.5 per cent of measured GNP

If:

(i) the net benefits of the legislation are deemed to exceed the costs;

(ii) the potential ecological benefits of mitigating global warming are at least as large as those from the earlier legislation; and

(ii) the legislation was solely directed to the preservation of natural ecosystems,

then the cost actually incurred to reduce ecological loss in the past would serve as a lower bound estimate for the increased losses associated with global warming. Assumption (i) does not seem problematic. Sentiment in most developed countries appears to favor strengthening rather than relaxation of environmental laws. The arguments presented above suggested that assumption (ii) is also valid. Assumption (iii), however, is not valid. Environmental laws are directed to human health objectives as well as to ecological concerns. Aesthetic and other concerns may also be important. Hence an application of this estimation procedure requires a finer partitioning of the social costs of existing legislation than is available at present.

For illustrative purposes, suppose that one-third of past environmental expenditures have been motivated by ecological concerns, and (following Nordhaus) that the experience of the United States is representative of that of the more developed countries as a group. It follows that mitigation of ecological damage associated with global warming would justify annual expenditures by these countries of at least 0.8 per cent of GDP.

These results contradict the arguments of Schelling (1991). He suggests that willingness to pay for environmental protection *per se* is very limited. This claim is made primarily on the basis of the observation that proposals to tax gasoline in the United States have had hardly any success. Schelling's argument would be convincing if it were true that the policy debate over gasoline taxes in the United States was a representative example of the political trade-off between direct economic benefits and the environment. In fact, the US gasoline tax debate is an extreme case. Most developed countries, unlike the United States, have imposed high taxes on gasoline. Further, the United States has adopted a number of costly measures aimed at achieving reductions in gasoline consumption (such as corporate automobile fuel economy standards) and the pollution associated with automobile use (as in the 1991 Clean Air Act). Many of the goals of these measures could have been achieved at lower social cost through a tax on gasoline (Crandall 1992). Finally, it may be observed that the resistance to gasoline taxation was equally vigorous when the good sought was not an improvement in the environment but a reduction in vulnerability to disturbances in oil supplies from the Middle East. In this case, again, the United States preferred to seek the goal through an alternative, apparently more expensive, route - the creation, deployment and use of a military capability to ensure the free flow of oil.

All of this leads to the conclusion that there is strong resistance to the taxation of gasoline in the United States. This is a problem for policymakers seeking to develop proposals for global reductions in CO2 emissions. However, it cannot be regarded as a representative illustration of the willingness of citizens in developed countries to trade off economic welfare for environmental protection.

Variability and uncertainty

It was shown above that uncertainty about the extent, pattern and timing of global warming has no effect on cost estimates derived using the optimal climate approach. This is not true for dynamic estimates. It is useful to distinguish between damage associated with predictable variations in the degree and rate of warming and damage associated with pure uncertainty.

The costs of predictable variability arise from the fact, demonstrated in Proposition 2, that damages are a convex function of the rate of warming. This means that the expected damage level is greater than the damage associated with the expected rate of warming.

Similarly, the convexity of the damage function implies that damages will be greater the more uneven is the rate of warming. Hence, cost estimates derived from the impact of the mean rate of warming will be biased downwards to the extent that rates of warming are higher in some areas than in others (assuming, as above, that this variation is uncorrelated with the existing temperature).

The same analysis applies to the distribution of warming over time. Most available projections imply a gradual and uniform increase in temperature. This is an artifact of the modelling techniques that are used. In fact, the rate of warming is likely to be highly non-uniform. One reason is simply statistical. The warming trend due to the build-up of greenhouse gases is super-imposed on ill-understood cyclical climatic fluctuations of varying periodicities (up to decades). During the period 1940 to 1980, a cyclical downturn was sufficient to offset the underlying trend presumed to be associated with the buildup of CO2. Conversely, in periods when an upward cyclical fluctuation is superimposed on the upward secular trend the rate of warming will be above the long run mean.

In addition to this statistical point it is likely that the climate system involves a wide range of non-linearities and threshold effects that are not captured by the climate models now available. These will also imply fluctuations in the rate of increase of temperature, particularly at the local level.

All of these effects arise on the assumption that the time-path of warming, though variable, is known with certainty. Uncertainty implies losses over and above those associated with the convexity of the damage function. The optimal outcome V^* in (6) above was derived on the assumption that the time-path of climatic change was known in advance at every point. The fact that the effects of global change are highly uncertain, especially at a local level, implies losses that are independent of risk-aversion or convexity of the damage function. In the presence of uncertainty, individuals will take actions in response to climatic change that turn out, *ex post*, to have been sub-optimal. These sub-optimal decisions may represent either a failure to take sufficient measures to deal with climatic change or excessive investment which turns out to have been unnecessary.

For example, farmers faced with a run of dry seasons must choose whether to continue to make investments in agriculture or to sell and move elsewhere. If *ex post*, the run of dry seasons turns out to have been a random fluctuation, those who sold will have made a costly error. Conversely if the climate has undergone a permanent change, those who persevered will regret their decision.

Another way of looking at this is that the information held by economic actors about the climate becomes more diffuse, and hence less valuable in the presence of a new source of uncertainty. Thus climate change may be regarded as destroying information. This information may in some cases be represented by formal probability distributions over temperature and rainfall derived from historical records. More frequently, it is the informal knowledge of particular local climates that is acquired by attentive individuals over a long period. Once again this is a dynamic problem.

These considerations relate to moderate variations in the rate of global warming. It is necessary, in addition to consider the possibility of an ‘apocalyptic’ outcome arising from unforeseen interaction effects. Such outcomes might include the melting of the Antarctic ice sheets or the diversion of the Gulf stream away from Northern Europe. Although the probability of such outcomes is low, the costs would be very large.

Concluding comments

Most assessments of the likely consequences of climate change have adopted a comparative static approach, in which the initial situation is compared to that which is expected to prevail after some given increase in temperature. Some assessments have been based on existing patterns of economic activity, thereby precluding adjustment. Going to the opposite extreme, Ricardian approaches incorporating the notion of a climatic optimum have, in effect, assumed that adjustment is costless.

In this paper, it has argued that the main costs of climate change will be costs of adjustment. Stocks of both natural capital and long-lived physical capital will be reduced in value as a result of climate change. This loss will be enhanced if the process of climate change is variable and stochastic.

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