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Exercises in hedging against extreme consequences of global change and the expected value of information

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This paper reports the implications for near-term global change policy of hedging against the extreme costs of low probability–high consequence events. Working with a full range of probabilistically weighted emissions trajectories and assuming complete resolution of uncertainty by the year 2020, the results support modest near-term carbon abatement policy that corresponds with a doubling of the efficient shadow price of carbon emissions. Assuming survey generated subjective likelihoods of extreme events, the efficient hedging shadow price can, for example, be as high as US$18 (US$1990) per tonne of carbon emitted by the year 2020 along the median emissions trajectory and US$28 per tonne along a 95th percentile trajectory. Copyright © 1996 Elsevier Science Ltd

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Researchers have generally felt that the 'real action' in the integrated assessment of climate change would really be found in the analysis of low probability events that would produce large and costly effects. The need to begin a systematic exploration of such events has become particularly acute recently, because many examinations of a wide array of relatively more likely scenarios have produced little support for vigorous efforts to abate greenhouse gas emissions over the near-term. Even analyses that abandon the cost benefit paradigm in the face of a marked inability to survey adequately the long list of potential non-market damages in favour of achieving certain concentration limits have offered little support for an activist stance in the late 20th century.

The issue for those who are uneasy with the 'do little early' lesson of existing analyses is not, however, that these analyses cannot be believed. Nor is it that the cost benefit methodology upon which most are based is inappropriate or that researchers have been co-opted by forces that oppose an active greenhouse policy. It is, instead, an issue of what to do about an uneasy feeling that the scientific research community has thus far missed something important – the unsettling notion that greenhouse induced warming might trigger some as yet unknown climate based event that would dramatically and permanently change our way of life for the worse. Focusing attention on what to do in the near-term, then, one precise issue raised by this uneasiness questions whether or not there might be some reason to try to hedge against such a calamitous change by buying some 'insurance'.

This paper reports on the results of one response to a call to explore just that issue offered by the Uncertainty Working Group of the most recent Energy Modeling Forum, EMF-14. It describes work that attaches three alternative specifications chosen probabilistically to reflect the very high range of climate based damages authored by the Working Group onto seven representative global economic scenarios chosen probabilistically to reflect the range of possible unregulated future carbon emissions. Optimal emissions trajectories, and associated carbon tax trajectories, are computed for each combination under the assumption that the future is revealed to global policy makers in 1995. Second best trajectories that assume that the truth about the future is not revealed to policy makers until 2020 are also computed. Comparing the two for each combination of emissions and damages gives some insight into the expected, discounted value of information and how it depends upon both the variables that drive future economic activity and variables that define potential economic damage. Focusing on the second best trajectories also offers some insight into the value of hedging and the degree to which near-term policy should respond to the potential of high consequence/low probability events.

The second section offers a description of the underlying model employed here. Dubbed the Connecticut (CONN) model, it is a global emissions model designed to accommodate probabilistic scenario analysis and produced by wedding the general supply and derived demand structure of the original Nordhaus–Yohe model[1] with the damage structure of the more recent Nordhaus DICE framework.[2] The third section reports on a process by which the full range of emissions futures supported by simulation across the uncertain parameterization of the CONN model can be summarized effectively by seven representative scenarios. Each representative is fully described, and the range of possibilities that they collectively span is compared with established projections from IPCC, EMF-14 and DICE.

The fourth section offers similarly complete descriptions of two sources of extreme events. One is global climate sensitivity reflected by the equilibrium temperature rise associated with a doubling of atmospheric concentrations; the other is damage sensitivity reflected by the percentage of world GDP that would be lost annually if the global mean temperature were to rise by 3 degrees through the year 2100. Both parameters had been given base values in the specifications of the alternative emissions trajectories, and the fourth section simply records high values for each. The relative likelihoods of base and high values are then drawn from surveys of expert opinion.

The fifth section finally reports some results. Focusing initially upon the median emissions scenario, it is clear that even a minimal potential of high climate sensitivity associated with high damages supports some modest hedging – hedging that is, in fact, reflected by moving the near-term carbon tax up from its base case specification by an amount that is disproportionately larger than the small likelihood of this doubly extreme event. Larger likelihoods of one extreme event or the other also support modest movement in the optimal carbon tax through 2020, although changing climate sensitivity alone produces the smallest hedge.

The Connecticut (CONN) model: an aggregate integrated model with energy

World economic output in any year t [the standard GDP denoted here by $X(t)$] is taken to be functionally related to the capital stock [$K(t)$], the size

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Malinowski to this and preliminary work. Tricia, in particular, spent long hours checking the numerical analysis of each scenario. All remaining errors therefore reside with the author.

[1]W Nordhaus and G Yohe, 'Future carbon dioxide emissions from fossil fuels' in *Changing Climate*, National Academy Press, Washington, DC, 1983

[2]W Nordhaus, 'Expert opinion on climate change', *The American Scientist*, Vol 82, pp 45–51, January/February, 1994a; W Nordhaus, *Managing the Global Commons: The Economic of Climate Change*, MIT Press, Cambridge, MA, 1994b

of population $[L(t)]$, and the consumption of fossil and non-fossil fuel $[E_c(t)$ and $E_n(t)$, respectively$]$ according to

$$x(t) = \Omega(t)A(t)K(t)^{\gamma}\{L(t)^{d(t)}[bE_c(t)^{\alpha} + (1-b)E_n(t)^{\alpha}]^{(1-d(t))\alpha}\}^{1-\gamma} \quad (1)$$

so that the elasticity of substitution between fossil and non-fossil fuel $[\sigma_{cn}]$ is given by $[1/(\alpha-1)]$. The share of output devoted to paying labour will change over time so that Equation (1) can be adjusted each year to approximate a more general constant elasticity of substitution production structure with a series of evolving Cobb–Douglas schedules. More specifically,[3] letting the share of output devoted to labour vary over time according to:

$$d(t) = [(k_2 P(t)^{[q/(q-1)]} + 1]^{-1}$$

with

$$k_2 = [(1-m)/m]^{[1/(q-1)]}$$

supports a general CES structure of the form

$$x = AK^{\gamma}[mL^q + (1-m)E^q]^{(1-\gamma)/q}$$

Of course, the initial share of labour is,

$$d(0) = [(k_2 P(0)^{[q/(q-1)]} + 1]^{-1}$$

As a result, the effective elasticity of substitution over time between labour $[L(t)]$ and energy $[E(t) \equiv E_c(t) + E_n(t)]$, denoted σ_{EL} is given by $[1/(q-1)]$ even though the production structure for any one year has $\sigma_{EL} = -1$. Note, in passing, that

$$P(t) \equiv \{[P_c(t)E_c(t) + (P_n(t)E_n(t)]/[E_c(t) + E_n(t)]\}$$

is the (weighted) average price of energy given the prices of fossil and non-fossil fuels $[P_c(t)$ and $P_n(t)$, respectively$]$.

This underlying structure contributes to the stock of integrated assessment models in several ways. First, it allows the CONN model to expand the range of uncertain driving variables by exhibiting a derived demand for two types of energy defined in part by elasticities of substitution which are not constrained to equal unity. Equation (1) will, by virtue of structure to follow, also allow uncertainty about technological change in the supply of energy to be brought to bear directly upon employment decisions even as it expands the set of substitution possibilities *vis-à-vis* other aggregate models like CETA and MERGE. Both of these possibilities were identified as among the most important sources of uncertainty in Nordhaus–Yohe,[4] but neither has yet to be explored fully in a complete integrated assessment context.

Trajectories for population $[L(t)]$ and neutral technological change $[A(t)]$ are given exogenously by:

$$L(t) = L_0 e^{l(t)t} \text{ with} \quad (2)$$

$$l(t) = (1-\delta_L)l(t-1) \text{ and} \quad (3)$$

$$A(t) = A_0 e^{a(t)t} \text{ with} \quad (4)$$

$$a(t) = (1-\delta_A)a(t-1) \text{ and} \quad (5)$$

The capital stock at any point in time $[K(t)]$ and the employment of fossil and non-fossil fuel $[E_c(t)$ and $E_n(t)]$ will be determined endogenously.

[3] G Yohe, 'Constant elasticity of substitution, production functions with three or more inputs', *Economics Letters*, Vol 15, pp 29–34, 1983
[4] Nordhaus and Yohe, *op cit*, Ref 1

The cost of warming is given by $\Omega(t)$. According to the Nordhaus structure[5] adopted by Cline,[6]

$$\Omega(t) = [1 + \Delta(t)]^{-1}, \text{ where} \tag{6}$$

$$\Delta(t) = a[T(t)/3]^{\theta} \tag{7}$$

is a function of temperature at time t $[T(t)]$.[7] It is $\Omega(t)$ that is anchored to aggregate damages associated with the 2.5°C increase in global mean temperature that is usually attributed to a doubling of concentrations.

The price of non-fossil fuel is given by

$$P_n(t) = P_{n0} + P_0 e^{[h(t) + \zeta(t)]t} \tag{8}$$

with $h(t)$ representing the rate of technological change in the supply of energy and $\zeta(t)$ reflecting the bias of technological change toward (or away from) non-fossil fuel. The price of fossil fuel is similarly given over time by

$$P_c(t) = P_{c0} + [g_0 + \{[g_1 R(t)]/[R - R(t)]\} e^{h(t)t} + \tau(t) \tag{9}$$

with

$$R(t) = \sum_{i=1}^{t-1} E_c(i) \tag{10}$$

representing cumulative fossil fuel consumption through year $(t - 1)$. In addition,

$$\tau(t) = \tau_d(t) z(t) \tag{11}$$

summarizes a range of the carbon tax policy options denominated in dollars per tonne of carbon emissions. Most analyses rely on full blown dynamic optimization packages, at this point, assuming complete knowledge of what the future holds *and* how it might be altered by inserting a policy wedge between the price of delivering fossil fuel (in this case) to the market and the price actually seen by the (derived) demanders. The CONN model, in contrast, is less heroic. It assumes that decision makers will understand how damages are related to changes in temperature and that temperature changes now and in the future will be driven by current carbon emissions; and so it assumes that the tax in any one year will be determined by how decisions makers quantify these understandings and act on their quantification.[8]

Suppose, for the sake of argument, that decision makers could monitor movement along Equation (7) precisely and assume that they would, in each period, add a tax to the unit price of fossil fuel that is equal to their expectation of the marginal damage of resulting emissions denoted here by $\Gamma(t)$. At any time t, the marginal damage estimate $[D'(\Gamma(t))]$ that they require could then be expressed mathematically by

$$D'(\Gamma(t)) = \sum_{k=t}^{\infty} f_k'(\Gamma(t))\beta\Delta'(T(t))\}/(1 + r + \delta_M)^k$$

where $f_k(\Gamma(t))$ represents their estimated relationship between emissions in year k and changes in temperature in any later year t (ie for $t > k$). The discounting captured here reflects both the applicable rate of interest and the 'depreciation' of carbon from the atmosphere. The airborne fraction, β, is included, as well, to reflect an immediate deduction of current emissions against atmospheric concentrations.[9]

[5]W Nordhaus, 'An optimal transition path for controlling greenhouse gases' *Science*, Vol 258, pp 1315–1319, November 1992; Nordhaus, 1994b, *op cit*, Ref 2

[6]W Cline, *The Economics of Global Warming*. Institute for International Economics, Washington, DC, 1992

[7]Other structures may be employed in lieu of Equation (7) as more understanding of potential damages is generated. As it stands, now, the parameters a and θ are determined by the estimated annual loss (in terms of percent of global GDP) that might be associated with an effective doubling of atmospheric carbon concentrations *and* some conjecture about how quickly those damages might be climbing at that (future) point in time. Cline *op cit*, Ref 6, and Nordhaus, 1994a, *op cit*, Ref 2, adopt a quadratic structure with doubling causing GDP to fall by 1.3%. As a result, $\theta = 2$ and $a = 0.013$

[8]There is a technical reason for avoiding complete dynamic optimization, as well. To our understanding, all solution packages require a complete and constant formalization of the production relationship; they cannot, therefore, be expected to accommodate the dynamic approximation procedure that allows for arbitrary elasticities of substitution between energy and labour *and* between two types of energy

[9]Experiments that compare applications of this information constrained second best computation scheme along the media emissions scenario with the original DICE results show reasonable convergence in emissions, concentrations, changes in temperature, and carbon taxes through 2100

Employment decisions in any year conform to the neoclassical fundamentals which set the marginal products of all inputs equal to their real, net input prices. Full employment over the very long-term means that Equations (2 and 3) always hold. Applying these fundamentals to capital, then

$$K(t) = \{[\gamma\Omega(t-1)x(t-1)]/[(r+\delta)]\}, \tag{12}$$

where δ represents the applicable rate of depreciation. Investment in any year t $[I(t)]$ must now cover not only depreciation, but also any net investment required to bring $K(t-1)$ up to the level $K(t)$ given in Equation (12); ie,

$$I(t) = K(t) - K(t-1) + \delta K(t-1) = K(t) - (1-\delta)K(t-1) \tag{13}$$

summarizes investment – the portion of GDP devoted each year to maintaining the appropriate capital stock.[10] Applying the same marginal product rules to energy,

$$E_n(t) = \{[(1-\gamma-\mathrm{d}(t)-\alpha)\Omega(t-1)x(t-1)]/[P_n(t)]\}, \text{ and} \tag{14}$$

$$E_c(t) = \{[\alpha P_n(t)]/[(1-\gamma-\mathrm{d}(t)-\alpha)P_c(t)]\}\,E_n(t)$$
$$= \{[\alpha\Omega(t-1)x(t-1)]/[P_c(t)]\} \tag{15}$$

characterizes the derived demands for energy consistent with the production schedule given in Equation (1).

Following the usual convention of imposing the savings equals investment conditions for macro-economic equilibrium, per capita consumption $[c(t)]$ is

$$c(t) \equiv [\Omega(t)X(t) - I(t)]/L(t); \tag{16}$$

Per capita consumption is known because Equations (2, 3, 12, 14, 15) combine with Equation (1) to set GDP $[X(t)]$ and Equation (13) sets investment $[I(t)]$. Assuming that utility displays constant relative risk aversion equal to unity in per capita consumption, then

$$U(c(t)) = \ln\{c(t)\},$$

and the *de facto* optimization envisioned in the construction of the 'optimal' policy works to maximize the discounted sum of $U(c(t))$. The policy parameters highlighted in Equation (11) will be chosen to maximize the discounted value of utility over time with ρ representing the applicable pure rate of time preference.

The damage side of the model is driven by emissions. Following the DICE construction,

$$\Gamma(t) = z(t)E_c(t), \text{ where} \tag{17}$$

$$z(t) = (1+g_z(t))z(t-1) \text{ and} \tag{18}$$

$$g_z(t) = (1-\delta_z)g_z(t-1). \tag{19}$$

Emissions are converted into atmospheric carbon concentrations $[M(t)]$ by

$$M(t) = \beta\Gamma(t) + (1-\delta_M)M(t-1). \tag{20}$$

In writing Equation (20), parameter β is the instantaneous airborne fraction for carbon and δ_M reflects a seepage factor. The DICE accommodation of the Schneider forcing model completes the portrait. Forcing $[F(t)]$ is, more specifically, represented by

$$F(t) = 4.1\{[\log(M(t)/590)]/\log(2)\} + O(t) \tag{21}$$

[10] Equality of savings and investment is implicit in this construction, so care needs to be taken in practice to see that Equations (12) and (13) do not lead to unreasonable changes in savings rates

where $O(t)$ represents other forces; they are, for the moment, taken to be exogenous. The temperature index $[T(t)]$ upon which damages depend in Equation (7) is related finally to forcing through the now standard two equation simplification of complex global climate models:

$$T(t) = T(t-1) + \{F(t) - \lambda T(t-1) - (R_2/\tau_{12})[T(t-1) - T^*(t-1)]\}/R_1 \text{ and} \quad (22)$$

$$T^*(t) = T^*(t-1) + \{T(t-1) - T^*(t-1)\}/\tau_{12}, \quad (23)$$

where the $T^*(t)$ variable reflects ocean temperature.[11]

Identification of representative scenarios

Table 1 highlights nine uncertain parameters over which preliminary Monte Carlo simulation was conducted and indicates the sources of their initial distributions. In each case, high, middle and low values were assigned subjective probabilities of 0.25, 0.50 and 0.25, respectively. For reasons that will become clear, subsequent modelling focused on the four parameters that contributed most to the range of estimates of emissions through 2100; the full set of values for these are recorded first.[12] Median values only are noted for the other five. These medians combined with the baseline parameterizations of Equations (17 to 23) from DICE to solidify the foundation for an exhaustive, probabilistically weighted sampling over the other four that adequately reflected the initial Monte Carlo outcomes of 500 randomly selected scenarios drawn from the larger set of 3^9 possible combinations.

The resulting 81 scenarios were ranked in order of emissions (in 2100) and partitioned into seven groups. Following a methodology for selecting 'interesting' scenarios described in Yohe,[13] these partitions were defined and representative scenarios were selected in a way that minimized the probabilistically weighted sum of the squared errors in emis-

[11]The damage component of the model parallels exactly the structure employed by Nordhaus in the DICE Model *op cit*, Ref 2

[12]Note that technological change in energy $[h(t)]$ and the elasticity of substitution between fossil and non-fossil fuel again energy, as in the original Nordhaus–Yohe work, *op cit*, is among the most significant sources of uncertainty

[13]G Yohe, 'Toward a general methodology for selecting "interesting" greenhouse scenarios', *Climate Research*, Vol 1, pp 169–177, 1991

Table 1. Sources of uncertainty – parameter location and specification.

Description	Location	Specification	Likelihood
(1)[a] Population	Equation (3)	$l(t) = (0.873)\,l(t-1)$	0.25 H
		$l(t) = (0.805)\,l(t-1)$	0.50 M
		$l(t) = (0.732)\,l(t-1)$	0.25 L
(2)[b] Technological change in energy supply	Equations (8, 9)	$h(t) = 0.01$	0.25 H
		$h(t) = 0.0$	0.50 M
		$h(t) = -0.01$	0.25 L
(3)[c] Depletion factor in fossil fuel price	Equation (9)	$g_1 = 145$ and $R = 21$	0.25 H
		$g_1 = 687$ and $R = 21$	0.50 M
		$g_1 = 1230$ and $R = 21$	0.25 L
(4)[d] Interfuel elasticity of substitution $[\sigma_{cn}]$	Equation (1)	$\sigma = -0.4$ and $\alpha = -1.50$	0.25 L
		$\sigma = -0.7$ and $\alpha = -0.43$	0.50 M
		$\sigma = -1.2$ and $\alpha = 0.17$	0.25 H
(5) General technological change	Equation (5)	$a(t) = (0.89)\,a(t-1)$	median
(6) Carbon content factor	Equations (17, 18)	$g(t) = (1.039)\,g(t-1)$	median
(7)[b] Technological bias toward fossil fuel	Equation (8)	$\xi(t) = 0.0$	median
(8)[g] Energy labour elasticity of substitution $[\sigma_{EL}]$	Equation (1)	$\sigma = -1.2$	median
(9)[h] Marginal airborne fraction	Equation (20)	$\beta = 0.64$	median

[a]Growth rates per decade. *Source:* Nordhaus and Yohe, *op cit*, Ref 1 and Nordhaus, *op cit*, Ref 2.
[b]Rate of change per year. *Source:* Nordhaus and Yohe, *op cit*, Ref 1.
[c]Reflection of depletion of the high resource estimate in Nordhaus and Yohe, *op cit*, Ref 1, fit to reflect the 1993 IEW poll results.
[d]Measure of the percentage change in fuel mix (fossil to non-fossil) associated with each 1 percent change in relative energy prices. *Source:* Nordhaus and Yohe, *op cit*, Ref 1.
[e]Rate of change per decade. *Source*: Nordhaus and Yohe, *op cit*, Ref 1 and Nordhaus *op cit*, Ref 2.
[f]Carbon emission per tonne of coal equivalent. *Source:* Nordhaus, *op cit*, Ref 2.
[g]Measure of the percentage change in energy consumption in proportion to labour employment associated with each 1 percent change in the relative price of energy with respect to the wage paid to labour; source: Nordhaus and Yohe, *op cit*, Ref 1.

[h]*Source:* Nordhaus and Yohe, *op cit*, Ref 1 and Nordhaus *op cit*, Ref 2.

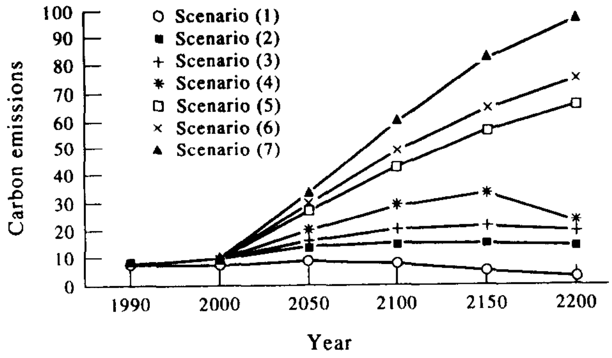

Figure 1. Carbon emissions (in billions of tonnes) for the seven representative scenarios.

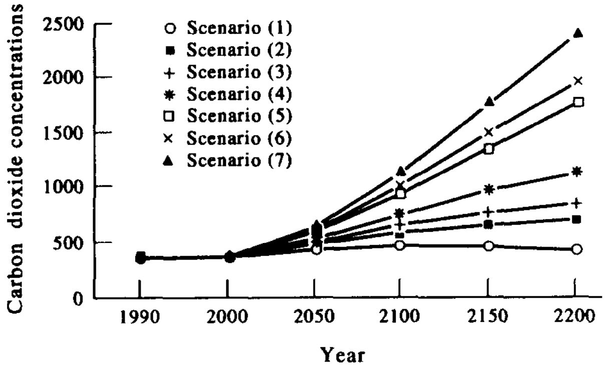

Figure 2. Carbon dioxide concentrations (in parts per million volume) for the seven representative scenarios.

sions (again, in 2100) involved in describing the entire distribution by a collection of only seven trajectories.[14] Figures 1 and 2 portray the selected emissions and concentration paths graphically, and Table 2 identifies their underlying specifications. The probabilities noted in column (1) are the sum of the likelihood weights of all of the scenarios housed in the indicated partition.

Since the scenarios described in Table 2 emerged from a process that artificially collapsed a potential of 3^9 runs from one specific model into a manageable set of scenarios deemed representative and 'interesting', it is reasonable to question the degree to which they reflect anything more than the idiosyncracies of the model, the selection process, or both. Table 3 performs the dangerous task of comparing these seven scenarios, expressed in terms of both carbon emissions and carbon dioxide concentrations, to several other ranges. It is comforting to note that the seven representative scenarios chosen here do reasonably well in reflecting the diversion of expert opinion. They fully span the emissions recorded by the IPCC in its six specified scenarios; indeed, approximately 20% of the likelihood range reported here exceeds the highest IPCC emission trajectory (IS92e). The seven selected here lie between the 10th

[14]The procedure that lead to the selection of seven representative trajectories also creates a specific partition of all possible trajectories – partitions that were also defined by the minimizing procedure. The procedure starts with an arbitrary partitioning for which error minimizing representatives were chosen. In the next step, the highest member of the lowest partition was moved to the next highest partition and the calculations redone. If the sum of squared errors fell, then another member was moved up; if not, then it was returned to the lowest partition. This trial and error method was applied to all of the partition boundaries until no more error reducing moves were available. There are theorems that describe when this procedure converges to a unique outcome. Their conditions appear to have been met by the collection of 81 emissions values, but confidence can be placed on the fact that starting from different initial partitions and working from both the bottom up and the top down produced the same results

Table 2. Specification of representative scenarios.

Scenario	Subjective likelihood	Population growth	Technological change	Depletion	Substitution elasticity
(1)	0.27	H	H	L	H
(2)	0.13	H	M	M	H
(3)	0.23	L	M	M	M
(4)	0.19	M	M	L	M
(5)	0.09	M	L	H	L
(6)	0.05	H	L	M	L
(7)	0.04	H	L	L	L

Table 3. Selected results – comparisons with conventional wisdom[a]

	Emissions in 2100	Concentrations in 2100
(A) Representative scenarios		
Median inputs	20.2	679
Scenario (1)	7.8	502
Scenario (2)	15.6	615
Scenario (3)	20.2	679
Scenario (4)	28.7	785
Scenario (5)	43.4	972
Scenario (6)	48.9	1044
Scenario (7)	59.9	1165
(B) IPCC scenarios		
Scenario IS92c	4.6	n/a
Scenario IS92d	9.9	n/a
Scenario IS92b	18.6	n/a
Scenario IS92a	19.8	n/a
Scenario IS92f	25.9	n/a
Scenario IS92e	34.9	n/a
(C) DICE[b]		
Tenth percentile	6.4	465
Median trajectory	24.1	671
Ninetieth percentile	82.5	1203
(D)[c] Energy Modeling Forum – 14		
Modeller's choice (low)	8.5	605
Modeller's choice (high)	32.0	1150
Standardized reference (low)	12.0	605
Standardized reference (high)	48.5	1550

[a]Emissions are given in billions of tonnes of carbon; concentration is parts per million volume.
[b]Values reported for 2095, actually, in Table 7.3 of Nordhaus, 1994b, *op cit*, Ref 2.
[c]Values estimated from graphical presentations of First Round EMF-14 results.

and 90th percentile DICE results in both emissions and concentrations, but they show much more potential on the 'high side' than the preliminary 'modeller's choice' sample from EMF-14. Comparison with even a full set of alternative scenarios would not constitute validation of these scenarios, to be sure. Table 3 offers some evidence that the seven scenarios described in Table 2 do, indeed, adequately span the range of currents opinion about what the future might hold.

Definition of low probability, high impact scenarios

The extreme cases against which hedging was considered were designed by the Uncertainty Working Group of EMF-14 in May of 1995 and summarized succinctly in a memo distributed to the Group by William Nordhaus and Alan Manne. This section summarizes the content of that memo[15] as it applies to the seven representative scenarios described above. Each extreme case was characterized in the memo by one or two variables across which careful surveys of experts had been conducted. As a result, the subjective, relative subjective likelihood of each extreme could be assessed. The first, climate sensitivity, was defined as the equilibrium temperature change that would occur if atmospheric concentrations of carbon dioxide were doubled. The second, warming damages, were defined to reflect the total economic cost (market and non-market) that would be felt if that doubling were to produce a 3 degree warming.

Table 4, reproduced from Nordhaus,[16] shows the summary statistics of two surveys of expert opinions. Based on these statistics, the Uncertainty Working Group design asked participants to quantify their high sensitivity cases by adding the survey difference between the conditional mean of the 5% tail to their base case values (ie, to add 2.3 degrees Celsius to the assumed climate sensitivity employed originally). In the results that follow, the IPCC best guess of 2.5 degrees characterized the base scenarios, and so a 4.8 degree equilibrium warming potential fixed the high sensitivity extreme. The Working Group design also asked partici-

[15]W Nordhaus, 'Notes on scenarios for uncertainty group', communicated June, 1995
[16]Nordhaus, *op cit*, Ref 15

Table 4. Characterization of the extreme cases[a]

Variable	Median	Standard deviation	Conditional mean of top 5%
Temperature sensitivity (denoted T)	2.80	1.4	5.1
Warming damages (denoted D)	1.75	3.3	13.6

[a]The median noted is the 50th percentile of the expected value of respondents' estimates. The standard deviation records the median of their standard deviation estimates. The conditional mean reflects the mean of values lying in the top 5% tail of all respondents' estimates; a log-normal distribution is assumed for damages and temperature sensitivity reflects the 97.5th percentile. Temperature sensitivity is the equilibrium increase in global mean temperature from a doubling of atmospheric carbon dioxide concentrations. Warming damages express the sum of the economic value of market and non-market effects associated with a 3 degree warming over the next century in terms of percentages of world GDP.

Sources Nordhaus, *op cit*, Ref 15.

Table 5. Specifications of the alternative scenarios

Case	Description	Subjective likelihood
U0	Base values for all parameters $T = 3$ degrees and $D = 1.6\%$	1-prob{Ui} with $i = \{1,2,3\}$
U1	High value for sensitivity *and* damages $T = 4.8$ degrees and $D = 12.48\%$	0.0025[a]
U2	High value for sensitivity only $T = 4.8$ degrees and $D = 1.6\%$	0.05
U3	High value for damages only $T = 2.5$ degrees and $D = 12.48\%$	0.05

[a]The likelihood of U1 climbing as high as 0.05 depending upon the correlation of climate sensitivity and economic damage.

Source: Nordhaus, *op cit*, Ref 15.

pants to 'scale up' their damage function by the survey ratio of the conditional mean of the 5% tail to the median value. Table 4 shows this ratio to be 7.8; the results that follow therefore associate the high damage extreme with a 12.48% loss of GDP – up from the 1.6% damage estimate upon which the representative scenarios were based.

Specifications of the extreme scenarios supported the definition of four alternative cases for each baseline scenario. Table 5 records the specific details. Notice that Case U1 is really a combination of U2 and U3; its relative likelihood, assuming that damages and sensitivity are independently distributed, is thus (0.05)2 = 0.0025. If a case were made that high sensitivity were positively correlated with high damages, however, then the subjectively likelihood of U1 would be higher – perhaps as high as 0.05 in the case of perfect correlation. The effect of this potential correlation on the value of information in confronting case U1 was investigated.

Hedging strategies and the value of information

Table 6 focuses initial attention on Case 3 – the median scenario. Part A details emissions, concentration and temperature trajectories without any regulation under the U0, U1, U2 and U3 assumptions described in the previous section. Notice that changes in the severity of damage and climate sensitivity effect all of the trajectories in the expected direction; increased damage slows economic activity and reduces emissions. Part B highlights optimally controlled emissions and their associated carbon tax trajectories for each assumption, and relates the resulting concentration and temperature consequences with each. These are the 'learn then act' (LTA) trajectories that presume perfect foresight in 1995; and so they correspond to policies that would be initiated now if it were known that U0, U1, U2 or U3 were, in fact, accurate descriptions of the future.

Part C reports the results of the 'act then learn' (ATL) hedging experiment for U1, U2 and U3 under the assumption that policy makers

Table 6. Description of the median scenario

Part A: Unregulated trajectories

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2em	5864	73001	8797	10324	11841	13314	147144	16024	17230	18327	19312	20187
U0CO2co	353	379	403	429	458	489	520	553	585	617	648	678
U0Temp	0	0.27	0.5	0.73	0.94	1.16	1.36	1.57	1.76	1.94	2.12	2.28
U1CO2em	5864	7233	8627	9992	11288	12478	13538	14457	15233	15873	16392	16806
U1CO2co	353	379	402	427	454	482	511	538	566	591	616	638
U1Temp	0	0.53	0.85	1.17	1.47	1.78	2.07	2.35	2.62	2.87	3.11	3.33
U2CO2em	5864	7297	8790	10308	11812	13266	14642	15921	17091	18146	19085	19912
U2CO2co	353	379	403	429	458	482	520	552	584	615	646	675
U2Temp	0	0.53	0.86	1.18	1.49	1.8	2.11	2.42	2.71	2.99	3.26	3.51
U3CO2em	5864	7259	8685	10110	11498	12814	14032	15134	16113	16968	17706	18335
U3CO2co	353	379	402	428	456	485	514	544	574	602	630	656
U3Temp	0	0.27	0.5	0.72	0.93	1.14	1.34	1.53	1.71	1.89	2.05	2.19

Part B: Optimal emissions and tax trajectories – act then learn

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2em	5864	7251	8519	9833	11065	12195	13243	14175	15024	15774	16459	17074
U1CO2em	5864	6609	6027	5866	5796	5771	5917	6164	6513	6897	7312	7718
U2CO2em	5864	7207	8312	9453	10407	11198	11871	12436	12937	13385	13813	14225
U3CO2em	5864	6898	6958	7303	7686	8036	8491	8937	9419	9862	10301	10701
U0CRT	0	1.74	4.18	8.07	11.46	15.07	19.21	23.46	28	32.43	36.84	40.92
U1CRT	0	24.5	58.96	120.73	163.2	198.13	226.81	247.24	263.57	275.66	286.4	295.84
U2CRT	0	3.17	7.37	15.67	23.26	31.91	41.58	51.65	61.92	71.82	81.17	89.61
U3CRT	0	13.46	32.95	60.15	78.96	94.59	110.01	123.18	136.43	148.27	159.99	170.55

Part C: Hedging trajectories for emissions, concentrations, temperature change and taxes – learn then act

Date of resolution of uncertainties – 2020 Pure rate of time preference = 3%; growth discounting to goods

Base case U0 0.9975 likelihood
High case U1 0.0025 likelihood

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2em	5864	7141	8345	9343	11056	12269	13305	14239	15074	15823	16495	17108
U1CO2em	5864	7074	8183	9042	6027	5027	5258	5649	6069	6504	7034	7551
U0CO2co	353	379	401	424	450	478	506	533	560	586	612	635
U1CO2em	353	378	399	422	431	435	440	445	450	456	463	471
U0Temp	0	0.27	0.5	0.71	0.91	1.11	1.3	1.48	1.65	1.81	1.96	2.1
U1Temp	0	0.53	0.84	1.14	1.39	1.58	1.73	1.85	1.96	2.05	2.14	2.22
U0CRT	0	2.86	6.92	13.71	11.08	14.84	18.92	23.3	27.8	32.36	36.76	40.95
U1CRT	0	2.86	6.92	13.71	210.49	238.44	256.98	272.09	284.5	287.58	290.8	293.47

Expected discounted value of perfect information = 5.29 billion dollars
Base case U0 0.95 likelihood
High clim Sens U2 0.05 likelihood

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2em	5864	7171	8436	9835	11078	12208	13255	14187	15034	15782	16466	17080
U2CO2em	5864	7167	8428	9466	10397	11192	11861	12431	12928	13381	13807	14223
U0CO2co	353	379	401	426	452	480	507	534	561	587	612	636
U2CO2co	353	379	401	425	449	473	496	519	540	560	579	597
U0Temp	0	0.27	0.5	0.71	0.92	1.12	1.31	1.49	1.66	1.82	1.97	2.11
U2Temp	0	0.53	0.85	1.16	1.45	1.73	2.01	2.25	2.49	2.71	2.91	3.1
U0CRT	0	2.32	5.45	9.02	11.41	15.03	19.17	23.43	27.99	32.42	36.84	40.93
U2CRT	0	2.32	5.45	9.02	23.28	32.01	41.61	51.74	61.95	71.88	81.18	89.64

Expected discounted value of perfect information = 0.7 billion dollars
Base case 0.95 likelihood
High damage 0.05 likelihood

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2em	5864	7077	8164	9048	11056	12319	13348	14282	15109	15857	16521	17130
U3CO2em	5864	7035	8059	8860	7717	7617	8156	8691	9248	9733	10229	10663
U0CO2co	353	378	400	422	449	477	505	532	560	586	611	635
U3CO2co	353	378	399	421	436	449	462	475	488	501	514	526
U0Temp	0	0.26	0.49	0.7	0.9	1.1	1.29	1.47	1.65	1.81	1.96	2.1
U3Temp	0	0.26	0.49	0.69	0.86	0.99	1.11	1.21	1.31	1.41	1.5	1.58
U0CRT	0	4.09	9.93	18.49	10.85	14.68	18.74	23.17	27.67	32.3	36.72	40.96
U3CRT	0	4.09	9.93	18.49	89.48	102.08	115.23	126.35	138.6	148.74	159.56	169.25

Expected discounted value of perfect information = 19.7 billion dollars

(1) view the likelihood of each as 0.25%, 5% and 5%, respectively and (2) understand that all uncertainty about the relationship between emissions and damage will be resolved in the year 2020. The expected discounted costs of hedging against these extreme cases is negligible in

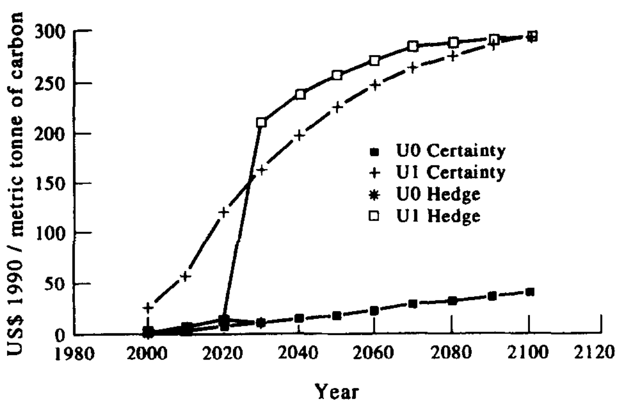

Figure 3. Carbon tax trajectories (shadow price of carbon in US$1990 per tonne carbon) in the U0–U1 comparison along scenario (3).

the U2 case, but climbs to nearly 0.1% of 1990 world GDP for U3.[17] The expected cost of hedging against U1 is only slightly greater than US$5 billion (US$1990) assuming a 0.25% subjective view of its relative likelihood, but that estimate is very sensitive to the correlation between high damages and high climate sensitivity. More will be made of this sensitivity shortly, but it is worth noting in passing even now that the expected cost would climb to more than US$91 billion (US$1990) if correlation were perfect and U1 had a 5% subjectively likelihood. This is an estimate that corresponds roughly 0.43% of 1990 world GDP.

Figures 3 and 4 display the corresponding tax and emissions trajectories for the U1 hedging strategy. They are typical of all of the results. The tax paths show a quick convergence back to the U0 path when the U0 state of the world emerges as expected in 2020, but also shows a slower convergence from well above the U1 track if the unlikely U1 future turns out to be true. Emissions along the hedging trajectory, meanwhile, run slightly above the U0 path after adjustment is made for a U0 revelation in 2020; but they track well below the U1 certainty trajectory far into the next century when the U1 eventuality materializes.

Table 7 displays the summary expected, discounted value of information statistics for all seven representative emissions scenarios or cases for all of the comparisons. The values generally climb with emissions for given elasticities of substitution between fossil and non-fossil fuel; ie, the values for Case 2 are higher than they are for Case 1, the values for Case 4 are higher than for Case 3, and the values climb from Case 5 through Case 7. The values do, however, fall as the elasticity of substitution rises in magnitude. Cases 1 and 2 are, in particular, characterized by $\sigma_{cn} = -1.2$; Cases 3 and 4 by $\sigma_{cn} = -0.7$; and Cases 5, 6 and 7 by

[17]The expected discounted cost of hedging is computed as the expected discounted value of perfect information in 1995 assuming (1) a 3% rate of time preference (ie, $\rho = 0.03$), (2) logarithmic utility in per capita consumption and (3) a standard Ramsey-style growth discounting procedure for goods and services that adds the observed annual rate of growth in per capita consumption to ρ. It is the difference between the expected net benefit of optimal policies applied to U0 and U1 (eg) separately (weighted by their respective relative likelihoods) and the expected net benefit of hedging with the same tax through 2100 and then correcting to the then reveal actual trajectory (again, eg, U0 and U1). Benefits are climate based damages avoided; costs are standard dead-weight loss areas.

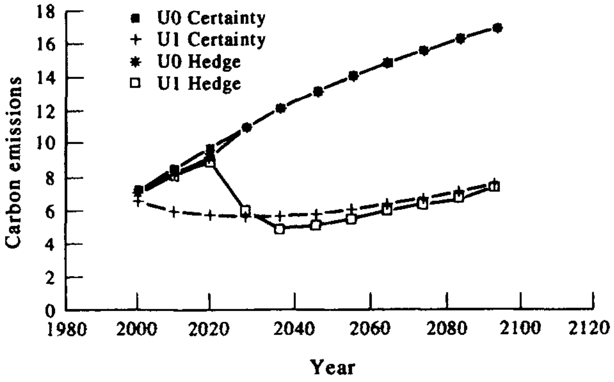

Figure 4. Carbon emissions (in billions of tonnes of carbon) along regulated trajectories in the U0–U1 comparison along scenario (3).

Table 7. Summary statistics for representative scenarios

Case scenario	Expected discounted value of perfect information[a] U0 versus U1	U0 versus U2	U0 versus U3
(1)	US$5.32 (US$94.80)	US$1.20	US$38.55
(2)	US$10.04 (US$164.45)	US$2.02	US$48.55
(3)	US$5.29 (US$91.30)	US$0.70	US$19.70
(4)	US$6.92 (US$124.20)	US$0.98	US$31.65
(5)	US$5.97 (US$107.15)	US$0.92	US$30.60
(6)	US$7.80 (US$136.45)	US$1.18	US$37.15
(7)	US$9.16 (US$164.80)	US$1.52	US$48.90

[a]Denominated in billions of US$1990. Note that net benefits are discounted according to the Ramsey growth discounting rule noted in the text with a 3% pure rate of time preference and logarithmic utility in per capita consumption. They presume that U1, U2 and U3 have relatively likelihoods equal to 0.0025, 0.5 and 0.05, respectively (ie, U2 and U3 are independent events with 5% likelihood). The values recorded in parenthesis in the U0 versus U1 comparison assume that U1 is as likely as either U2 or U3 (ie, that U2 and U3 describe perfectly and positively correlated events).

$\sigma_{cn} = -0.4$. This is consistent with standard dead-weight loss results from the first principles of micro-economic efficiency in (eg) optimal commodity taxation that supports taxing inelastically demanded goods most heavily; and it certainly supports a more general conclusion. The expected value of perfect information can thus be expected to be largest not only as emissions climb for given expectations about our ability to effect fuel substitution in the future, but also in circumstances when that ability is expected to be greatest. Quite simply, the errors involved in not accurately exploiting that ability, especially in the near-term, can be expensive.

Figure 5 highlights a second general result. It presents, graphically, the degree to which the value of information for the U0–U1 comparison depends upon the assumed independence of the two high consequence events. If, in particular, U2 and U3 are independent events with individual subjective likelihoods of 5%, then their joint likelihood in U1 is 0.25%. The values reported in Table 7 for U3 make that assumption. If U2 and U3 were positively correlated, however, then their joint likelihood would climb (as high as 5% under the assumption of perfect correlation). As a result, the expected discounted value of perfect information could rise dramatically – not by the full 20-fold factor, because policy adjustments would also be forthcoming, but almost. Table 8, for example, records the full complement of trajectory statistics for U1 under the perfect correlation assumption; and Figure 6 compares the corresponding tax trajectories. Note that the hedging taxes are higher through 2020 given perfect correlation, and so they converge more gradually against the U1 certainty path and more abruptly against the U0 certainty path.

Focusing finally on near-term policies, several observations can be offered based upon patterns that are displayed in Table 6 for the median scenario, the hedging taxes for the year 2020 listed for the U0 certainty,

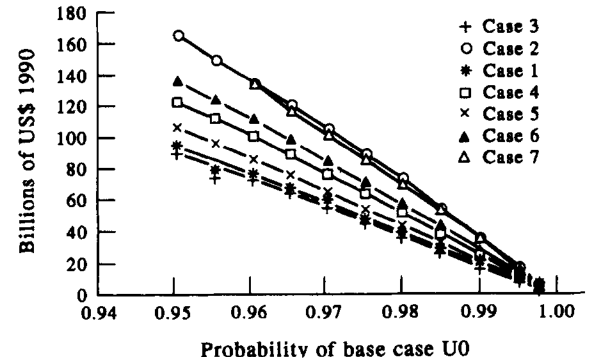

Figure 5. Expected present value of perfect information in the U0–U1 comparison given a 3% utility discount rate.

Table 8. Hedging against U1 with a 5% likelihood

Date of resolution of uncertainties – 2020   Pure rate of time preference = 3%; growth discounting to goods
Base case U0   0.95 likelihood
High case U1   0.05 likelihood

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
U0CO2e	5864	7022	8023	8683	11046	12373	13394	14328	15146	15893	16548	17155
U1CO2e	5864	6954	7867	8403	5977	5164	5386	5748	6154	6580	7088	7584
U0CO2c	353	378	399	420	447	475	503	532	559	585	611	635
U1CO2e	353	378	398	418	427	433	438	443	449	456	463	470
U0Temp	0	0.26	0.49	0.69	0.89	1.09	1.28	1.46	1.64	1.8	1.96	2.1
U1 Temp	0	0.52	0.84	1.13	1.36	1.55	1.7	1.83	1.94	2.03	2.12	2.21
U0CRT	0	5.1	12.4	24.98	10.59	14.52	18.53	23.05	27.52	32.25	36.66	40.98
U1CRT	0	5.1	12.4	24.98	200.47	229.62	250.53	266.98	280.19	285.09	289.81	293.82

Expected discounted value of perfect information = 91.3 billion dollars

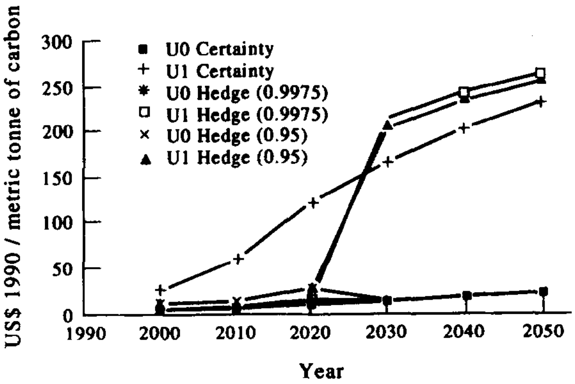

Figure 6. Carbon tax trajectories (shadow price of carbon in US$1990 per tonne of carbon) for alternative U0–U1 comparisons along scenario (3).

U1 (0.25% and 5% weights) and U3 cases that are recorded in Table 9, and the near-term hedging taxes for U3 cases that are reported in Table 10. Notice from Table 6, first of all, that recognizing a 5% chance of extreme climate sensitivity alone (Case U2) has a very small effect on near-term policies. Carbon taxes that incorporated some hedging strategy are higher than baseline taxes for all seven scenarios, to be sure, but they continue to be small well into the next century. Indeed, only in the

Table 9. Hedging taxes in the year 2020 for the representative scenarios[a] Cases U1 (with 0.25% and 5% probabilities) and U3.

Scenario	Base	U1 (0.25%)	U1 (5.00%)	U3 (5.00%)
(1)	US$7.80	US$14.98	US$22.16	US$17.23
(2)	US$7.96	US$15.89	US$27.24	US$18.01
(3)	US$8.07	US$13.71	US$24.98	US$18.48
(4)	US$8.34	US$17.10	US$25.86	US$19.16
(5)	US$9.18	US$20.92	US$29.73	US$23.79
(6)	US$9.51	US$21.71	US$33.91	US$26.23
(7)	US$9.53	US$21.75	US$33.97	US$27.84

[a]Denominated in US$1990 per tonne of carbon.

Table 10. Hedging taxes for the U3 comparison[a]

Scenario	2000	2010	2020
(1)	US$3.50	US$9.53	US$17.23
(2)	US$3.79	US$9.92	US$18.01
(3)	US$4.09	US$9.93	US$18.49
(4)	US$4.38	US$10.09	US$19.16
(5)	US$4.67	US$10.75	US$23.79
(6)	US$4.96	US$11.46	US$26.23
(7)	US$5.26	US$12.17	US$27.84

[a]Denominated in US$1990 per tonne of carbon.

U2 case are the hedging taxes so small relative to the U0 taxes that correction beyond the year 2020 simply slows the rate of increase of the tax instead of causing it to fall (at least through, say 2040 or so).

By way of contrast, extreme damage estimates can have a dramatic effect on near-term policies even when they are taken alone (Case U3). Table 9 shows hedging taxes that are more than twice the optimal taxes that would be applied if it were known with certainty that U0 would accurately describe the future along low emissions scenarios [eg, Scenarios (1) through (4)] and nearly three times as high along highest emissions scenarios [Scenarios (6) and (7)]. The hedging response to the 5% threat of U3 is, in fact, larger than it is for U1 when the joint probabilities work independently to give U1 a likelihood weight of 0.0025. Even then, however, near-term taxes are roughly 80% higher than they are along the baseline certainty trajectories for low emissions scenarios as again more than 100% higher along high emissions scenarios.

This is perhaps a curious reversal in rank, but it is easily explained in terms of the relative likelihood of the extreme event. Recall that the extreme event in the U1 comparison, a confluence of high climate sensitivity *and* high damages, is only 5% as likely as the extreme event in the U3 comparison, high damages alone. Moreover, the expected ranking would hold if the two parts of U1 were perfectly correlated. In that case, U1 would carry a 5% likelihood, and the hedging taxes could be more than 300% higher than along the baseline certainty cases. Expressed differently, manipulation of the model shows that the taxes that emerge from U1 and U3 would be nearly identical if U2 and U3 were sufficiently correlated to support a joint likelihood for U1 of 1%.

Concluding remarks

Timely information about the future has economic value that is directly proportional to the expected (net) benefits of policies designed to exploit its content. These types of policies garner the welfare gains associated with avoiding mistakes that otherwise would have been made – gains that persist even when they are discounted in the accounting of future costs and/or benefits *and* diminished by the small likelihood of potentially extreme events. Careful consideration of the value of information also produces some insight into how to hedge in the face of the lack of timely information. Indeed, the benchmark against which the value of perfect information should be measured includes optimal hedging against all the futures with quantifiable subjective likelihoods.

The results reported here offer insight into the expected value of information about two potential sources dire consequences from global warming events – extreme climate sensitivity and extraordinarily high economic damage. Taken individually and in concert, the expected value of knowing now whether either or both will occur (ie, the cost of hedging through 2020 in anticipation of finding out then that either or both is actually occurring) climbs across alternative emissions futures as long as increase emissions are the result of driving variables like population and fossil fuel depletion. If higher emissions are the result of lower abilities to substitute out of fossil fuels as their price increases, however, then the expected value of information can fall because the economic cost of setting an incorrect policy (and thus the economic value of setting a more correct policy) is actually smaller.

Translated into questions of near-term policy, hedging against low probability/high consequence events could be a reason for adopting some relatively modest short-term carbon abatement policy. A prudent strategy might be one that recognizes the U3 comparison as most significant, since stories that support some sort of positive correlation between high damages and high climate sensitivity are difficult to tell. In that case, Table 10 shows that a modest carbon tax set to grow to the US$3.50 to US$5.00 (per tonne of carbon) range by 2000, the US$9.50 to US$12 range by 2010 and the US$17.00 to US$19.00 range in 2020 might be most appropriate. In fact, setting near-term policy as if hedging strategies were to be computed for the median case would result in taxes that would track through the middle of these ranges. Only Scenarios (5), (6) and (7), with a combined relative likelihood of less than 20% drawn from the simulation model, show marked divergence from this path; and this appears only in the last decade when, presumably, the relative likelihood of a very high emissions path could be assessed more accurately.