Uncertainty, Climate Change and the Economic Value of Information: An Economic Methodology for Evaluating the Timing and Relative Efficacy of Alternative Response to Climate Change with Application to Protecting Developed Property from Greenhouse Induced Sea Level Rise

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Uncertainty, climate change and the economic value of information: an economic methodology for evaluating the timing and relative efficacy of alternative response to climate change with application to protecting developed property from greenhouse induced sea level rise[1]

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Increased atmospheric concentrations of radiatively active gases (e.g., carbon dioxide, various chlorofluorocarbons, methane, nitrous oxides, etc...) are expected to cause mean global temperatures to rise 2 °C to 5 °C over the next century (Schneider and Rosenberg, 1988). The effects of this greenhouse warming are likely to be widespread, but our current understanding of their potential dimension and their ultimate social, economic and political impacts is clouded with enormous uncertainty. Figure 1 displays, for example, a range of estimates for greenhouse induced sea level rise that have been reported in various publications over the past five years. In light of the disagreement shown there, a recent Report to Congress by the U.S. EPA (1989) advanced a range of greenhouse induced sea level rise through the year 2100 running from 50 centimeters on the low side to 150 centimeters on the high side; note that the upper boundary of the EPA range is 200% larger than the lower boundary and is deemed equally likely on the basis of the best information available in 1989. Researcher de Q. Robin (1987) had previously recorded an even larger range, expecting something between 20 and 165 centimeters of sea level rise attributable to greenhouse warming. Schneider and Rosenburg (1989) followed with more conservative expectations, suggesting cumulative sea level rise between 10 and 100 centimeters over the next 110 years, but could do no better than a 10 to 1 ratio between high and low extremes.

The degree of uncertainty exhibited by these estimates is dramatic, but it is also quite typical of the current state of our understanding, or lack thereof, across the entire spectrum of possible climate change effects.[2] The fundamental question in responding to the possible effects of climate change is therefore one of determining if any response should be undertaken, or even anticipated, given that we are so unsure of exactly what the future might hold. It is a question of very long term decision making or anticipation under conditions of overwhelming uncertainty for which 'we currently have no guidelines' (White, 1988). More fundamentally, it is a question of keeping the weight of uncertainty from totally hamstringing any and every response strategy, on the one hand, or leading us into undertaking expensive and ultimately unwarranted action, on the other.

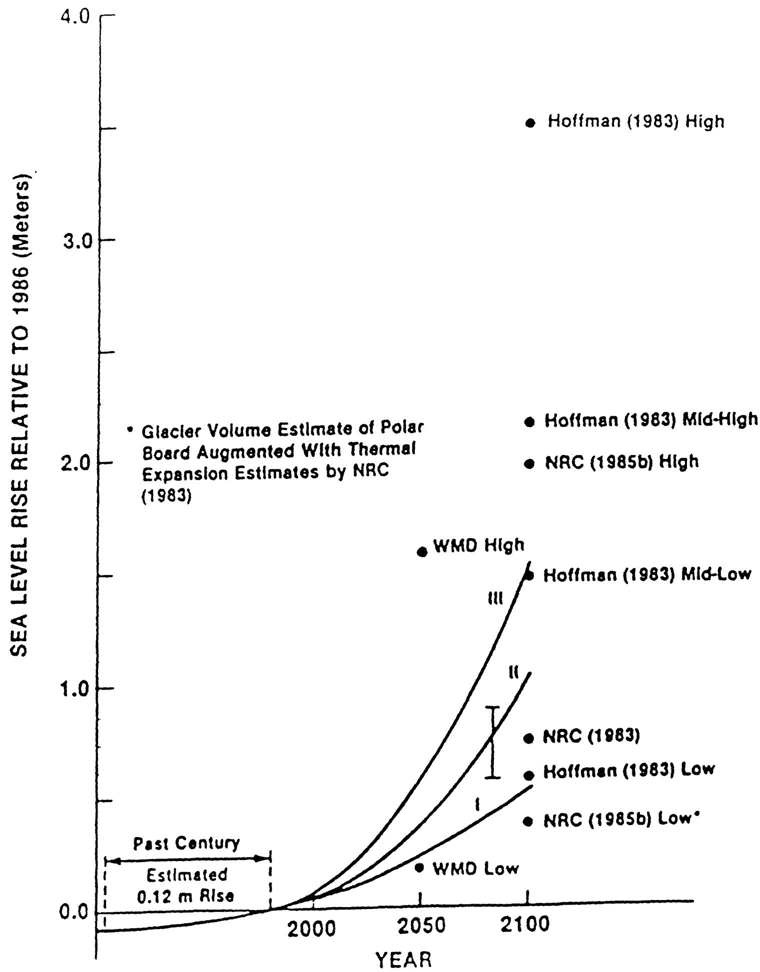

Fig. 1.

Response to climate change might be averting (policy intended to reduce the greenhouse effect by, e.g., reducing emissions of one or more of the offending gases) or adaptive (policy intended to cope with one or more of the potential effects) either by explicit design or as the serendipitous consequence of some other policy.[3] Evaluation of the efficacy of any averting response, even though it would be imposed globally in all likelihood, should certainly be based upon some aggregate measure of regional effects scattered around the globe; and it should certainly include the potential for complementary adaptive response which might be undertaken simultaneously. Adaptive responses would most likely be enacted on a local or regional level, by way of contrast, so they would require even more detailed measures of region specific effects to support their evaluation. In either case, analysis of possible reaction to the threat of climate change must be soundly based on an understanding of local and regional consequences of global influences (MacCracken, et. al., 1989).

Returning to the sea level rise example to illustrate this point, note that the relative merits of various adaptive responses to higher seas would have to be evaluated on the basis of the local economic ramifications of the full range of possible global sea level scenarios. They should therefore depend upon a vector of site specific characteristics: the geographical distribution of developed and undeveloped property, the value of that property, the potential for moving structures and/or protecting property, the underlying trends in natural subsidence, and so on. They should also depend upon a plethora of variables whose influence extends well beyond the boundaries of the specific site; e.g., scientific parameters which relate gas concentrations to global warming, global warming to climate change, and climate change to land-based ice melt and the thermal expansion of the oceans, to name just a few.

The issues raised by climate change are also dominated by their time dimension. It should be clear, as a result, that their potential economic effects would be expressed most efficiently if they were summarized in terms of time dependent and scenario contingent subjective distributions of potential economic cost based upon our best *current* understanding of the underlying uncertainties and correlations. It should be equally clear, however, that confining our attention to what is currently understood will reveal only part of the story. The world will certainly learn more about what the future holds as we move forward in time, so a second fundamental question obtains – one of determining the value of that information and its effect on our ranking of the various response options under consideration.

The value of new information which might, for example, allow us to distinguish across the range of climate change scenarios *prior to the need to respond* and thus inform both the structure and the timing of our response should be investigated. It should be expected that the value of such information would be different for different anticipated policies. Moreover, assuming that one type of information might be uncovered rather than another could easily alter the relative effectiveness of the entire set of possible options and lead a decision maker to anticipate a completely different set of response strategies. Set in the context of questions which we need to address even now, the value of new information is closely linked to the value of waiting to respond.[4]

Taking all of this complication to heart, it is easily understood why a thorough analysis of the response anticipation problem requires a methodology by which we can:

1. produce a ranking of alternative response options given current information;
2. suggest the anticipated timing of those options given current information;
3. suggest how the ranking and timing results based on current information

might change in the future as we learn more about what might be happening;
4. evaluate the value of new information that may alter the ranking and timing of potential response; and
5. suggest directions for which the results of future scientific and social scientific research might be most valuable.

Only by making progress in handling these tasks will be able to begin to answer more general questions of timing and planning. Can we, for example, wait to respond to climate change, or must we act now? If we choose to wait, what should we do in the meantime? Should we plan to deal with the extreme possibilities of climate change, or can we focus on responding to our best guess at what the future will bring? Will adaptive response be endogenous to the system, or should we anticipate a need to make conscious decisions at some point in time? How much will adaptive response reduce the magnitude of needed and contemporaneous averting response? How might the potential costs of climate change and/or our response to climate change be distributed? The list goes on and on.

Section I of this paper will outline the structure of a methodology within which progress can be made in confronting this list of tasks. Its inspiration is drawn, in part, from Marshak and Radnor (1972). Subsections will provide both an explicit suggestion of how to rank response options based on current information *and* means of extending the procedure to accomodate the potential economic value and ranking implications of new information. Section II illustrates the applicability of the procedure by considering two alternative means of protecting Long Beach Island, New Jersey, from greenhouse induced sea level rise. Two concluding sections highlight general insights which can be drawn from the application and the limitations of the data which currently exist.

I. A formal methodology

Let the future trajectory of some vector of state variables denoted

$$y_t = y_t(\theta_t; \gamma_t)$$

be distributed at each point in time according to $h_t[\theta_t, \gamma_t]$, with θ_t and γ_t representing vectors of random variables which produce, respectively, long and short terms stochastic effects on y_t.[5] For long term planning purposes, it is convenient to let the γ_t reflect 'white noise' along any potential trajectory and consider only $y_t = y_t(\theta_t)$ in the context of the marginal distributions for the θ_t:

$$f_t(\theta_t) = \int_{\gamma_t} h_t[\theta_t; \gamma_t]\, d\gamma_t .$$

Implicit in this convenience is the notion that white noise can be ignored in the long term planning process. While this assumption may be benign in many circumstances in which long term decisions are being evaluated, care should be taken to note that it could easily mask serious signalling problems when endogenous responses are included in the set of possibilities. Simply expressed, endogenous responses should depend upon correctly identifying long term trends in either the y_t directly or in the θ_t; significant levels of noise in the signal for either or both could certainly make this sort of accurate identification of the trends extremely difficult to achieve.

It should also be noted that the potential effects of climate change are sometimes associated with extreme, short term events which appear as 'noise'-deviations around a long term trajectory. There are, in fact, circumstances for which this is exactly the case. Agriculture comes to mind; it is an example for which climate is usually thought to be the long term phenomenon of interest, but for which weather is its critical short term manifestation. Heat and/or water stress, created by day to day weather patterns which may be correlated to climate but which are not climate, *per se*, are the primary source of concern. The key in such cases is to trace changes in the relative frequency of extreme events caught in the noise (e.g., weather) to changes in the long term climate variables which give trend to that noise.[6]

To continue with the formal characterization, let the cost associated over time with y_t be reflected by $C_t = C_t\{y_t(\theta_t)\}$.[7] Any action or sequence of actions $a_t[y_t(\theta_t)]$ taken over the course of the future in response to y_t will involve some stream of expenses $\phi_t\{a_t[y_t(\theta_t)]\}$ and achieve a corresponding stream of benefits equal to the cost avoided at any point in time:

$$\Gamma_t\{y_t(\theta_t); a_t[y_t(\theta_t)]\} = C_t\{y_t(\theta_t)\} - C_t\{y_t(\theta_t) \,|\, a_t[y_t(\theta_t)]\}.$$

The expected present value of the net benefits of some future response (or series of responses spread into the future) computed at time t_0 with a social discount rate β is then simply

$$E\{PV[a_t; f_t(\theta_t)]\} = \int_{t_0}^{\infty}\!\!\int [\Gamma\{y_t; a_t\} - C\{a_t\}] f_t(\theta_t) d\theta_t e^{-\beta t} dt. \tag{1}$$

This is the appropriate ranking criterion, but its application is extremely 'information intensive.' Application of equation (1) clearly requires (i) a time series of the cost of enacting a response at a specific time in the future, (ii) a time series of the beneft that such a response might create measured in terms of the potential costs of climate change that would be avoided, (iii) a subjective distribution of the important state variable whose effect is being investigated, and (iv) an operative social discount rate.

I.1. A ranking procedure

The expression recorded in equation (1) is extremely general. It is, in fact,

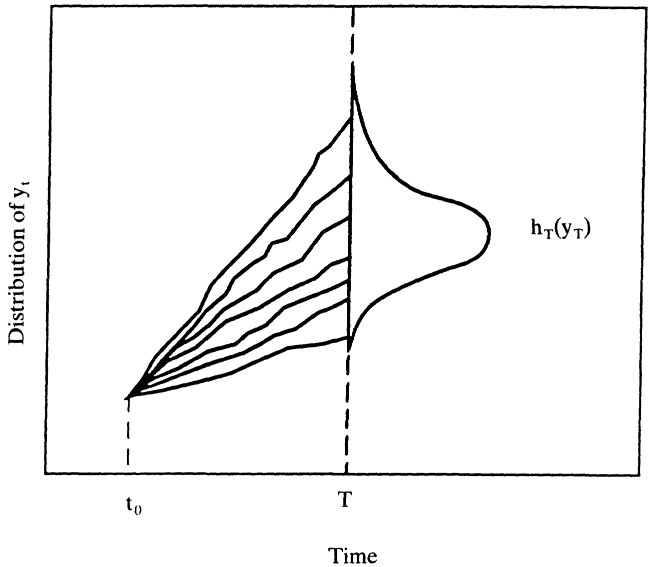

Fig. 2.

almost so general that it is useful only as a symbolic representation of the correct objective function. Thinking about the functional structure of some of those responses can, fortunately, produce a more illuminating formulation. Recall that we are considering strategies for future responses armed only with a collection of subjective distributions of the state variables y_t and an imperfect understanding of how the underlying random variables θ_t will drive them into the future (the $y_t(\theta_t)$ functions). Figure 2 displays just such a distribution for a single variable y_t, and shows how it can produce, for each point T in the future, a subjective conditional distribution $h_T(y_T)$ for y_T (a distribution for y_t given that $t = T$). Distributions like $h_T(y_T)$ are the usual representations of the uncertainty with which we view the future, but they are not usually the most effective conditional distribution of future uncertainty to apply to an analysis of potential policy response.[8]

Many responses will, as a matter of practice, be triggered in the future only when certain state variables cross specific critical thresholds which can be identified even now. We need to ask, in such cases, not only questions of what and how, but *when*. It makes sense, as a result, to focus on the orthogonal conditional distribution: a distribution $g_c(t)$ of timing for some given threshold value y_c. Figure 3 illustrates how the desired $g_c(t)$ distribution (a distribution of t given that $y_t = y_c$) might be constructed for the same distribution $y_t(\theta_t)$ drawn in Figure 2.

Returning to the formal problem, consider a univariate vector of state variables (i.e., let $y_t = y_t$) and let the structure of the planning process suggest a partioning of the range of $g_c(t)$ into intervals $\{I_1^t, \ldots I_n^t\}$. There exists a corresponding partitioning of the range of sequences of the θ_t which bring y_t

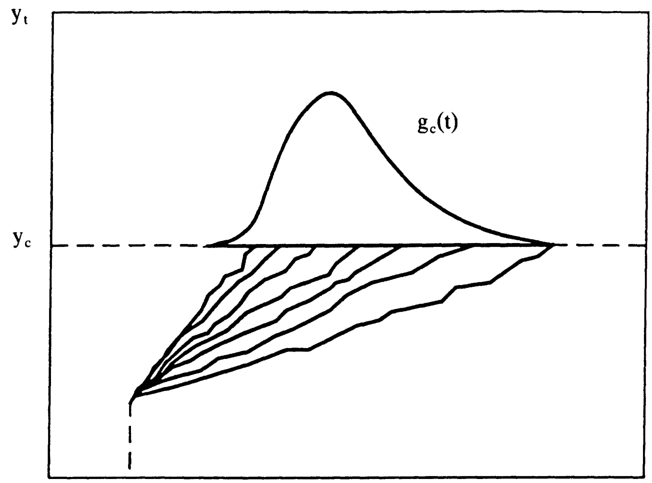

Fig. 3.

across the threshold within the specified intervals I_t^i. Let that partitioning be given by $\{{}_1\theta_t, \ldots, {}_n\theta_t\}$. The partitioned expected present value represented in equation (1) can then be written

$$E_P\{PV[{}_1a_t, \ldots, {}_na_t; f_t(\theta_t)]\} =$$

$$\int_{t_0}^{\infty} \sum_{{}_i\theta_t} \int \{[\Gamma\{y_t; {}_ia_t\} - \Phi\{{}_ia_t\}] f_t(\theta_t) d\theta_t\} e^{-\beta t} dt, \qquad (2)$$

where ${}_ia_t$ represents the response that would be anticipated in partition ${}_i\theta_t$. For perfectly endogenous responses, there is no difference between (2) and (1); the partitions simply produce a distinction with no content. For other responses whose timing and magnitude are critically dependent upon speed and momentum with the threshold is reached and past, however, there is a distinction of potentially large significance.

To see why, let some response be generically defined and represented by a_t. Implicit in the definition of a_t are issues of both timing and scope, so ${}_ia_t^*$ can be thought to represent the best configuration of action a_t that can currently be anticipated given that y_t is expected to cross the threshold in interval I_i^t. If decision makers were forced, as they are frequently, to anticipate enacting one response strategy based on current information, then they should rank each according to the discounted values of expected net welfare assuming that it is enacted regardless of the future trajectory of y_t. That is to say, using the notation of (2), the various ${}_ia_t^*$ should be ranked according to

$$E_P\{{}_ia_t^* \mid f_t(\theta_t)\} = E_P\{PV[{}_ia_t^*, \ldots, {}_ia_t^*; f_t(\theta_t)]\}; \qquad (2a)$$

the notation $E_P\{_ia_t^* \mid f_t(\theta_t)\}$ notes explicitly that the best current information embodied in the density function $f_t(\theta_t)$ is used in computing expected value. Response $_ia_t^{**}$ such that

$$E_P\{_ia_t^{**} \mid f_t(\theta_t)\} \geqslant E_P\{_ja_t^* \mid f_t(\theta_t)\} \text{ for all j.} \tag{2b}$$

is then the best single option of time and scope that can be anticipated given current information. Note, as well, that (2b) defines a mechanism by which the best timing of various responses can be investigated as part of the ranking procedure. It is enough to include sets of responses differentiated only by the timing of their anticipated enactment among the list of various $_ia_t$ to be considered. The dominate $_ia_t^{**}$ would then define not only the best response strategy, but also when it could be expected to be most efficient.

I.2. The value of perfectly discriminating future information

Equation (2) provides an easy means of sorting out both the effect of new information (which allows decision-makers to differentiate across the range of time intervals) on the best anticipated response and its resulting economic value. Suppose, for example, that future research held out the possibility of uncovering information which would allow a decision maker to tell, prior to acting, whether some critical threshold would be crossed in a subset of early intervals $I^1 = \{_1I_t, \ldots, {}_mI_t\}$ or in its complement set of late intervals $I^h = \{_{m+1}I_t, \ldots, {}_nI_t\}$. There is, of course, an equivalent partitioning of the range of θ_t given by $\theta_t^1 = \{_1\theta_t, \ldots, {}_m\theta_t\}$ and $\theta_t^h = \{_{m+1}\theta_t, \ldots, {}_n\theta_t\}$. Repeating the process just described above for restricted sets of intervals I^1 and I^h would then yield two best choices: $_1a_t^*$ for I^1 and $_ha_t^*$ for I^h. The expected present value of choosing response strategies contingent upon discovering either I^1 or I^h would then be

$$E_P\{I^1; I^h \mid f_t(\theta_t)\} = E_P\{PV[_1a_t = {}_1a_t^*; \ldots; {}_ma_t = {}_1a_t^*; \\ {}_{(m+1)}a_t = {}_ha_t^*; \ldots; {}_na_t = {}_ha_t^*]\}; \tag{3}$$

and the value of the information that provided the ability to discriminate would be

$$E_P\{I^1; I^h \mid f_t(\theta_t)\} - E_P\{_ia_t^* \mid f_t(\theta_t)\} \geqslant 0. \tag{4}$$

It is, of course, possible that $_ia_t^{**} = {}_1a_t^* = {}_ha_t^*$, in which case the difference recorded in equation (4) is exactly zero. Strict inequality should be expected whenever, as should be the rule, $_ia_t^{**} \neq {}_1a_t^* \neq {}_ha_t^*$.

Information that discriminates across the range of possible futures can have value, and it can alter the timing and character of any response that might be anticipated. Constructing a catalog of the best response strategies for a collection of possible distinguishable partitions of set of intervals $\{I_1^t, \ldots, I_n^t\}$ would provide insight into the sensitivity of anticipated responses, including their timing and their scope, to this sort of new information. Recording, as well, the value of the information that informs those strategies would indicate the areas of research that would be most fruitful.

I.3. The value of Bayesian learning

The new information considered in the previous section was perfectly discriminating without influencing the density function $f_t(\theta_t)$. Other types of new information are, of course, possible. A Bayesian learning process could, for example, be envisioned moving along the trajectories of y_t which lead to crossing the threshold during some interval ${}_iI_t$. Such a process would not influence our current best view of the range and relative likelihoods of threshold intervals, but it would alter future subjective distributions of those intervals. This is clearly information of a different character, but the problem of estimating its value can, in the present framework, be thought of as one of estimating the value of discriminating information which is not perfectly accurate.

Notice that equation (3) uses $f_t(\theta_t)$ to index the relative likelihood of I^1 and I^h and assumes implicitly that ${}_ka_t^*$ will correctly be employed only in I^k $(k = 1; h)$ and that the signal presumed there perfectly discriminates between I^1 and I^h sometime in the future even though our best information at time t_0 is captured entirely in $f_t(\theta_t)$. Bayesian learning, especially given white noise reflected in γ_t, cannot be expected to produce such perfect discrimination. It will, instead, produce only posterior distributions based on interim experience which will only make I^1 and I^h more or less likely. The key, of course, is that future decisions will be based on that updated information; and it is those decisions based on future information which must be evaluated given what we know at time t_0.

To model these decisions, let $p_t(\theta_t; t_1; \theta_t^k)$ represent the marginal posterior distribution of θ_t that would be derived in period $t_1 > t_0$ given interim experience consistent with $\theta_t \in \theta_t^k$. Evaluation of any response sequence ${}_ia_t$ would then, in period t_1, be based upon $E_P\{{}_ka_t \mid p_t(\theta_t; t_1; \theta_t^k)\}$ for any θ_t^k. Best choices ${}_k\hat{a}_t$ would then be characterized by

$$E_P\{{}_k\hat{a}_t \mid p_t(\theta_t; t_1; \theta_t^k)\} > E_P\{{}_ka_t \mid p_t(\theta_t; t_1; \theta_t^k\} \text{ for all } {}_ka_t \tag{5a}$$

and define the anticipated response, its timing, and its scope. The current view of the expected social value of the ${}_k\hat{a}_t$ should therefore include their anticipated expected social value given experiences consistent with $\theta_t \in \theta_t^k$, but weighted by current expectations of the relative likilihoods of the θ_t^k; i.e.,

$${}_BE_P\{{}_k\hat{a}_t\} = \sum \int_{\theta_t^k} f_t(\theta_t) d\theta_t E_P\{{}_k\hat{a}_t \mid p_t(\theta_t; t_1; I^k)\} \tag{5b}$$

should be used to evaluate the present value of using future Bayesian information to inform response decisions.

Notice that the composite expected present value defined in (5) provides direct access to a measure of the economic value of Bayesian information. Compared to the case with no extra information for which ${}_{i}a_t^{**}$ was selected as the best single option that could be anticipated with current information, the value of Bayesian information is simply

$$ {}_{B}E_{P}\{{}_{k}\hat{a}_t\} - E_{P}\{{}_{i}a_t^{**} \mid f_t(\theta_t)\} \geqslant 0. \tag{5c} $$

It should be non-negative, of course, because ${}_{i}a_t^{**}$ was a choice in the decision process characterized in (2). It could be zero, though, if the Bayesian process produced too little information (because, e.g., the white noise was too large to glean much information about the distribution of the θ_t). Why? Because the posterior distributions would nearly match $f_t(\theta_t)$ and the ${}_{k}\hat{a}_t$ would all match ${}_{i}a_t^{**}$. It could also be zero if the cost and benefit schedules implicit in the definition of both ${}_{B}E_{P}\{-\}$ and $E_{P}\{-\}$ were linear.[9]

Generating catalogs of the sort suggested at the end of Subsection I.2 should be able to produce the same sort of sensitivity and value insight for anticipated Bayesian learning as it did for orthogonal learning. It should, as a result, provide some insight into the present value of waiting, watching and learning more about what the future might bring (not so much from targeted research as from simple monitoring and observing. Notice that the structure created here should also be applicable to new information that does not result from Bayesian learning but which nonetheless falls short of being perfectly discriminating. In the former instance, we glean some insight into the value of waiting (and learning while we wait); in the latter, we gain some understanding of where we should be devoting research efforts.

II. Application to protecting Long Beach Island — an illustrative example

Long Beach Island is a barrier island lying off the shore of New Jersey. It is approximately 23 miles long, and varies in width from roughly 1000 feet to slightly more than 3200 feet. Except for dunes on the ocean side, almost all of the island lies within 10 feet of sea level. It is, nonetheless, heavily developed, with total property value generally put in the neighborhood of $2 billion ($1989). Data have been developed, reflecting both the economic vulnerability of the island in the absence of any policy response or any market response to the threat of inundation, on the one hand, and the cost of employing three different protection strategies, on the other (see Yohe, 1989, for vulnerability data and Weggel et. al., 1989, for protection cost statistics).

This section applies the analytical tools developed in Section I to these data to evaluate the relative efficacy of two of the options investigated by the EPA – (1) raising the island as the sea level rises [and endogenous response] and (2) building a dike and associated infrastructure when the sea level rise crosses a predetermined threshold [a conscious response requiring anticipation and preparation]. The rate of sea level rise will be taken to be the critical, random state variable. The value of perfectly discriminating and Bayesian information will be considered in the context of a distribution of possible sea level rise scenarios drawn from current divergent opinion. The point is not to recommend the better choice for protecting Long Beach Island; a dike would ruin the beachfront and thus dramatically erode property values in ways that are not captured in the benefit estimates employed. It is, instead, to provide an example which demonstrates the applicability and feasibility of the formal methodology described above.

II.1. Sea level rise scenarios

A distribution of projected sea level rise attributable to greenhouse warming through the year 2100 was derived from the range of expert opinion reflected in the Figure 1.[10] A log-normal distribution fit the divergence of opinion well, exhibiting a mean of the natural log of greenhouse induced sea level rise through 2100 in centimeters of 4.55 and a standard error of 0.88. The one standard error range around the mean increase of 94 cm was therefore taken to be 39 cm on the low side and 227 cm on the high side.

A five cell discrete equivalence of this distribution (i.e., a distribution which preserved both the mean and the standard error of the natural log of sea level rise through 2100) is provided in Table 1. For the probability values shown in column 2, the third column shows the time coefficient α_j for each scenario which drives total sea level rise according to the EPA functional representation:

$$SL_j(t) = 0.4(t\text{-}1986) + \alpha_j(t\text{-}1986)^2. \tag{6}$$

The first term in equation (6) reflects local subsidence for Long Beach Island of 0.4 centimeters per year; the second term reflects greenhouse induced sea level rise. The final column of Table 1 indicates the year during which a 43 cm threshold (a threshold whose importance will become clear) would be passed for each scenario.

Table 1. Sea level rise scenarios for Long Beach Island.

(1) Scenario	(2) Probability	(3) Coefficient α	(4)[a] SLR(2100)	(5)[b] Threshold year
A	0.1	0.00144	64	2069
B	0.2	0.00318	86	2055
C	0.4	0.00718	137	2039
D	0.2	0.01595	252	2026
E	0.1	0.03539	504	2015

[a] In centimeters of total sea level rise.
[b] Weggel (1989) sets 43 cm as the threshold at which a dike system would be required.

II.2. Data – the benefit side

Table 2 records the total economic vulnerability data reported in Yohe (1989). Tax maps were employed to determine the current value of property (including land and structure) that would lie below the spring mean high tide for various levels of sea level rise. Property that would be in jeopardy because of beach erosion was also included, so the statistics registered total in Table 2 reflect a measure of what, as the island now stands, would be 'in the way' of rising seawater and its derivative effects. They will, for present purposes, also be taken as a measure of potential economic cost attributable to sea level rise.

This procedure will, of course, be a source of error, since it ignores the possibility of a wide range of complications: further economic development prior to inundation, response to true economic depreciation in anticipation of inundation, etc. Done correctly, the benefit side of any protection scheme should be taken as the true economic cost avoided through its enactment, including the effect of each of these complications on the translation of vulnerability to opportunity cost. Absent this translation, the vulnerability avoided must be considered an order of magnitude representation of potential benefits that may be too high if significant market-based adjustment in response to climate change were possible.

Table 2. Economic vulnerability for Long Beach Island.

(1) Sea level rise (cm)	(2) Incremental vulnerability (\$ million)	(3) Total vulnerability (\$ million)
0–15	15	15
15–30	40	55
30–45	225	270
45–60	192	462
60–90	381	843
90–120	705	1548
120–180	385	1932

Source: Yohe (1989).

II.3. Data – the cost side

Weggel and his colleagues (1989) have meanwhile produced estimates of the costs involved in three protection strategies for Long Beach Island; two will be considered here. The first, raising the island in place in response to observed sea level rise, has three sources of cost: fill (sand available at \$6 per cubic yard along a scenario which sees a 200 cm rise in sea level attributable to greenhouse warming by the year 2100), raising structures (at \$5000 per structure to accommodate the higher ground), and replacing roadways (which must lie on top of the new higher ground). Since these costs are correlated directly with sea level rise, producing time series of costs for scenarios other than the one which produces 200 cm over 115 years is a simple matter of algebra. The only wrinkle employed in the translation involves the price of fill. A unitary short run price elasticity of supply was assumed, but only for more rapid scenarios. The price of fill would rise if demanded more quickly than anticipated along the 200 cm baseline, but would not fall if demanded more slowly (i.e., $6 represents a long run competitive price equal to a minimum sustainable average cost).[11]

Starting when total sea level rise from 1986 reaches 13 cm, Weggel et. al. estimate the volume of sand (in cubic yards) required in year t along a 200 cm greenhouse induced scenario to be

$$V_{200}(t) = 73534 + 5273(t\text{-}1986) + 0.427(t\text{-}1985)^2.$$

The 200 cm scenario is, meanwhile, defined by

$$SL_{200}(t) = 0.4(t\text{-}1986) + \alpha_b(t\text{-}1986)^2,$$

where $\alpha_b = 0.01424$. The volume requirement along any scenario j is therefore

$$V_j(t) = 73534 + 5273(\alpha_j/\alpha_b)^{1/2}(t\text{-}1986) + 0.427(\alpha_j/\alpha_b)(t\text{-}1986)^2.$$

Price times volume then provides the appropriate estimate of the cost of fill as a function of time along any scenario:

$$CF_j(t) = P_j(t)V_j(t).$$

Similar manipulation of the Weggel estimates of the cost of raising structures and replacing roads (in $ million) produces:

$$CS_j(t) = 13.65(\alpha_j/\alpha_b)^{1/2} + 0.01(\alpha_j/\alpha_b)(t\text{-}1986) \text{ and}$$

$$CT_j(t) = 2.8 + 0.133(\alpha_j/\alpha_b)^{1/2}(t\text{-}1986),$$

respectively. The $C_t(a_t[Y_t(\theta_t)])$ function required in equation (1) for raising the island was taken to be the sum of these three cost components for the specified scenarios.

Allowing, for purposes of illustration, that the benefit achieved by protection along any scenario j could be represented in first approximation by the current economic value of property preserved by preventing inundation, the net present value of raising the island is easily computed. The first section of Table 3 records these values for the five scenarios identified in Table 1 for a 3% social rate of discount. The final entry notes the expected net present value computed according to equation (1). Raising the island is found to be an economically viable option which could be undertaken depending upon stress exerted on the public budget constraint by other claims to public resources.

The second option considered here proposes (1) building a dike around

Table 3. Expected present value of raising the island or constructing a dike and drainage system.

(1) Policy description	Scenarios (2) A	(3) B	(4) C	(5) D	(6) E	(7) Expected present value
I. Raising the island	13.0	32.5	129.7	252.6	355.6	145.8
II. Anticipating a dike in:						
2015	37.4	67.1	157.0	309.2	463.0*	188.1
2026	38.7	68.9	158.9	311.9*	88.8	152.5
2039	40.8	71.0	160.7*	117.6	88.8	115.0
2055	42.0	72.6*	52.7	117.6	88.8	72.2
2069	43.4*	14.6	52.7	117.6	88.8	60.8

the island when sea level rise (from both greenhouse warming *and* natural subsidence of 0.4 cm per year) reaches 43cm and (2) operating an interior drainage system from that time on. The dike, itself, was estimated to cost $285 million. Some small cost derived from raising existing bulkheads would be incurred before the dike were brought on line, and expenditures equalling $2.5 million would be required each year to maintain and operate the drainage system.[12] The issue here, then, not only questions the adviseability of building the dike in lieu of a continuous strategy of raising the island, but also ponders the best timing for its construction.

Any scenario of sea level rise would, in this case, imply a planned date for constructing the dike which could be correct, early, or late. If it were correct, then the stream of costs would be well defined by the Weggel estimates. If the planned date turned out to be early, though, policy makers would be prepared too early, and could simply wait to build the dike until it were seen to be necessary; the cost scenario of the Weggel estimates would then simply be extended further into the future. If the planned date turned out to be late, on the other hand, inundation damage would be suffered prior to the construction of the dike and the drainage system. It was assumed arbitrarily that it would take at least 5 years from the recognition of immediate need to the completion of the dike unless the dike was originally planned to be completed in the interim.

Protecting Long Beach Island by constructing a dike and its requisite drainage system could hardly be considered a continuous, contingency response to the threat of sea level rise. It would require considerable prior planning and development, a protracted period of construction, a commitment to continuous maintenance after construction, and a future stream of enormous expenditure of public revenues. It would require, in short, a wide margin of preparation time. Any current consideration of the economic value of such an option must, therefore, be based upon an anticipation of exactly when a specified threshold of sea level rise will be crossed so that the timing the financial expenditure and its associated flow of benefits can be appropriately assessed.

Recall that Table 1 identified, in its last column, the years during which the threshold for Long Beach Island, calculated by Weggel to be roughly 43 cm, would be achieved along five representative scenarios of sea level rise. Since the scenarios were selected to reflect a current subjective distribution of potential sea level trajectories, these years can be viewed as representing the associated distribution of dates at which construction of the dike system must be completed to adequately protect the island. They define, as a result, five representatie responses which are differentiated solely on the basis of timing and which span the range suggested by the current subjective distribution of sea level rise.

Columns (2) through (6) in the second section of Table 3 record, for each scenario, the discounted net benefit of anticipating the completion of the dike system for each of the dates listed in Table 1. The highlighted diagonal, therefore, shows the maximum discounted benefit for being right along each scenario; i.e., each entry along the diagonal displays the present value of the stream of net benefits that should be expected if the anticipated date of completing the dike were to exactly match the threshold year during which it would be first needed. Figures below the diagonal show the discounted net benefits that should be expected if the critical thresholds were breached earlier than anticipated. The dike would, in such cases, be finished too late to totally protect the island and some economic value embodied there would be lost to increasing inundation. They are all the same because the dike would be hurriedly completed in the same time frame along each scenario, and the damage caused would correspond to the scenario, itself. Figures above the diagonal meanwhile reflect the discounted net benefit of being ready too early; resources would then have been expended too quickly in the preparation, and an inefficient period of waiting for the threshold to be achieved would have to be endured.

The expected discounted net benefit for each anticipated date of completion, computed from columns (2) through (6) according to equation (2a), is provided in the final column of Table 3. These are estimates currently available in the absence of any further information. Ranging from $188.11 (million) for anticipating completion of the dike system in the year 2015 down to $60.77 (million) for planning completion in 2069, they clearly show a marked dominance for planning to take early action. Building in anticipation of the extreme case depicted in Scenario E even dominates the endogenous island raising response examined in Subsection C; the endogenous response shows, more specifically, an expected discounted value of net benefits equal to $145.77 (million) – more than 22% lower. The insurance of preparing for the early completion of the dike system, even at the expense of being prepared too early and even given the subsequent expense of actually constructing the dike, is seen to be less costly in terms of expected, discounted expenditure than the continuous process of raising the island year in and year out.[13]

II.4. The value of discriminating information

Table 4 shows the results of contemplating the discovery of some new information that would, in the future, allow policy makers to distinguish perfectly between subsets of the five threshold scenarios listed in Table 1. Each section of the table presents results for a different partitioning of the 5-cell discrete distribution of sea level scenarios, and records the expected discounted value of anticipating the completion of the dike system at the threshold time indicated, given that a scenario within the partition occurs. In other words, each entry shows the results of applying equation (2a) to a limited range of possible scenarios.

Before reviewing the content of Table 4, it is perhaps prudent to picture exactly what sort of information might accomplish the partitioning modeled there. Better understanding of the thermal expansion of the ocean, better estimation of the correlation between concentrations of various gases and earth's radiation budget, progress in identifying the 'greenhouse fingerprint', etc... could all be envisioned, as opportunities for new insight which will allow decision makers to limit the range of possible sea level futures; that is to say, each has the potential to rule out certain scenarios which, given today's information, are still plausible. They have no idea whether or not such information is forthcoming, so there is no reason to adjust the current subjective distribution of sea level scenarios. They are, quite simplty, investigating how much it would be worth, now, if it were to appear sometime prior to the need for any response.

Table 5 shows the best contingent choices for anticipating the completion of the dike system for the four partitions defined in there. Compared with the

Table 4. Expected present values for constructing a dike – differentiating information.

	Anticipated year for completing the dike				
	2015	2026	2039	2055	2069
Differentiating (A) from (B, C, D, E)					
(A)	37.4	38.7	40.8	42.0	43.4
(B, C, D, E)	204.9	165.1	123.2	75.6	62.7
Differentiating (A, B) from (C, D, E)					
(A, B)	57.2	58.9	60.9	62.4	24.2
(C, D, E)	244.2	192.6	138.1	76.4	76.4
Differentiating (D, E) from (A, B, C)					
(A, B, C)	114.2	116.0	117.9	56.9	40.5
(D, E)	360.5	237.5	108.0	108.0	108.0
Differentiating (E) from (A, B, C, D)					
(A, B, C, D)	157.6	159.5	117.9	70.4	57.7
(E)	463.0	88.8	88.8	88.8	88.8

uninformed expected present value of \$188.11 (million) associated with planning completion by 2015, none of the partitions appears to be much of an improvement. Computed according to equation (4), the most valuable partition distinguishes between early and late scenarios at roughly the 70th percentile and returns an expected discounted value of

[\$190.71 − \$188.11] (million) = \$2.6 (million).

Looking at the value of perfect discrimination (\$191.82 million), though, there was not much room for improvement.[14]

That is not, however, the entire story. Referring back to Table 5, notice that the expected present value of planning the construction of the dike system changes only slightly in the 25 year period between 2015 and 2039. Information that distinguishes early from late around the 70th percentile could therefore ease some of the budgetary pressures that might otherwise be felt by the federal government if their share of the expense had to be committed within a more limited time frame. Given a larger window for anticipating response in Long Beach Island, it should be easier to smooth total protection expenditures devoted to what could be a large collection of projects scattered all along the coastline over a period of time best measured in decades. Devoting some effort to research that might accomplish even this sort of crude division in the potential range of sea level outcomes could, therefore, have some indirect payoff beyond its \$2.6 million contribution to expected net benefit. Finally, note that Table 5 suggests a greater payoff to research designed to distinguish rapid sea level rise from slow sea level rise than to research designed to identify the extremes.

Table 5. Best timing with differentiating information.

Differentiation	Best timing	Expected present value
I. (A) vs (B, C, D, E)		
(A)	2069	\$188.7 (million)
(B, C, D, E)	2015	
II. (A, B) vs (C, D, E)		
(A, B)	2055	\$189.7 (million)
(C, D, E)	2015	
III. (A, B, C) vs (D, E)		
(A, B, C)	2039	\$190.7 (million)
(D, E)	2015	
IV. (A, B, C, D) vs (E)		
(A, B, C, D)	2026	\$189.9 (million)
(E)	2015	
V. Complete	Correct time	\$191.8 (million)

II.5. The value of Bayesian information

The year 2015 is the first threshold year identified above, suggesting a potential waiting period of roughly 30 years (from the 1986 base used by Weggel) during which Bayesian learning might better inform potential response decisions. Steve Schneider has suggested (Rosenburg and Schneider, 1989) that the scientific complexities of climate change are so enormous that convergence in our view of its effects cannot be expected over the next two or three decades. In modeling a Bayesian learning process along any of the five sea level scenarios identified in Table 2, it therefore seems reasonable to assume that experience over the next 30 years, extrapolated through the year 2100, can be viewed as supporting observations drawn from a lognormal distribution exhibiting the same variance as today's. Since climatologists look at 30 year intervals to assess and define changes in climate, we can also expect at most the equivalent of one such observation.

Representing the current view of the distribution of the natural logarithm of sea level in the year 2100 by

$$\ln\{SL(2100)\} \sim N(m_0, \sigma_0),$$

the result of 30 years of movement along scenario k yielding an estimate $x_k = \ln\{SL_k(2100)\}$ should therefore be a new, contingent distribution

$$\ln\{SL(2100)\}_k \sim N(m_k, \sigma_k) \qquad (7)$$

with

$$m_k = 0.5(m_0 + x_k)$$

and

$$\sigma_k^2 = (\sigma_0^2\sigma_0^2)/(\sigma_0^2 + \sigma_0^2) = 0.5\sigma_0^2.$$

If the x_k are taken to equal the natural log of the 2100 values indicated in Table 1 and $\sigma_0 = 0.88$, then each of the five scenarios must be assigned different discrete probability values consistent with equation (7) and thus contingent upon which scenario defined the 30 year experience from 1986 through 2015. Table 6 records those values.

Table 6. Relative frequencies after Bayesian learning.

	Scenario				
Experience	A	B	C	D	E
Scenario A	0.38	0.35	0.18	0.07	0.02
Scenario B	0.17	0.37	0.28	0.15	0.03
Scenario C	0.07	0.14	0.58	0.14	0.07
Scenario D	0.03	0.15	0.28	0.37	0.17
Scenario E	0.02	0.07	0.18	0.35	0.38

Table 7. Expected present value of response options after Bayesian learning.

(1) Policy description	Scenarios (2) A	(3) B	(4) C	(5) D	(6) E	(7) Expected present value
I. Raising the island	64.5	99.1	138.4	195.5	249.4	145.8
II. Anticipating a dike in:						
2015	96.7	135.5	175.7	248.3	317.9	188.5
2026	90.8	125.7	150.5	184.8	173.2	152.7
2039	79.3	98.5	125.5	115.5	109.6	115.2
2055	60.1	69.1	65.4	85.6	90.4	72.4
2069	41.2	47.9	57.4	76.9	86.3	60.9

Table 7 indicates the resulting expected discount values of all six options (raising the island and constructing a dike during the five alternative years) contingent upon the learning that would occur in the first 30 years along each scenario in columns (2) through (6). Each has been computed according to equation (5a). The final column records the current view of their expected discounted net benefit based on equation (5b). The figures recorded in column (7) of Table 7 reflect, when matched against the comparable figures in Table 3, our best idea of how much Bayesian learning would be worth for each policy given our current subjective distribution across the trajectories that will be doing the 'Bayesian teaching.' The differences representing that value, defined by equation (5c), are small; but that again is a function of both the effective contingency response that was assumed when the dike was anticipated too early or too late and the linearity of the resulting net benefit schedule. The real news buried in Table 7 can be uncovered by noticing that the variation in expected net benefit shown across the rows in columns (2) through (6) is much smaller than the corresponding variation in net benefit of the uninformed decisions of Table B.3. An objective function displaying any sort of risk aversion would therefore applaud the results of the Bayesian process.

III. Qualitative insights

A complete analysis of various response options to climate change according to the procedures outlined in previous sections is extremely data and labor intensive. There are, however, a few general insights which can be drawn from even its short history of application to real world problems. It should be emphasized, first of all, that contingency responses need not always be preferred to more discontinuous reactions which have specific starting dates and which require considerable preparation prior to enactment and continued maintenance after enactment. In the Long Beach Island case, for example, anticipating the need for a protective dike at either of the two earliest dates suggested by the underlying distribution of future greenhouse induced sea level rise dominated the perfectly contingent option of raising the island as needed.

There are two reasons for this dominance that translate into general insights into the ranking of contingent and discrete reaction strategies. First is cost, and the degree to which it is discounted into the future. A contingent policy response typically starts early and must be continued, perhaps with increasing intensity, indefinitely into the future. It might be dominated, therefore, by a more discontinuous policy option with limited preparation expense, a delayed anticipated time of enactment, and/or (much) more modest acceleration in continuing operating expense after enactment.[15]

The second reason, while related to cost, can be explained more clearly in terms of the ease with which even a discontinuous response strategy can be designed as a low cost 'insurance policy.' If, for example, preparations for enacting a discrete policy response could be undertaken inexpensively and well in advance, then it could pay to turn it into a contingency response by preparing for the earliest date suggested by the underlying subjective timing distributions and 'putting it on the shelf' for use as needed. If, as would likely be the case, the response were not required at that early date, then it could simply be held in abeyance until the date uncertain in the future when it will be required. Conversely, if discontinuous options were expensive even in preparation, more expensive to enact and maintain once their time came, and/or so complex that quick initiation in emergency situations would be even more prohibitive, then pure contingency response become relatively more attractive.

Consideration of the differences between contingency and discrete responses can also be used to generate some intuitive insight into the value of future information and the value of waiting to respond. Future information, generally provides economic value, but its value can be eroded by alternative contingency responses and/or by discrete responses which can be constructed to serve a contingency function by standing ready for enactment after some early and careful preparation. In either case, more information has little effect because response is essentially ready for whatever happens even without knowing what is coming. Waiting and monitoring is, therefore, relatively more attractive only in those cases for which contingency responses and scarce in the initial list of options to be considered and/or discrete responses require elaborate and expensive preparation.

Contingency policies are best designed in anticipation of earliest need. There is still expense involved in getting them on the shelf, though, and that expense could be minimized if the notion of earliest need could be more clearly understood. Future information which would divide the threshold timing interval between early and late at roughly the 50th percentile would provide the largest differentiation between earliest need contingent upon that information, and would therefore be most valuable. When dominant policies defy, by their very nature, structuring their enactment as a contingency response, however, the opposite differentiation proves most valuable. It would be mroe important, in such cases, to allow decision makers to perceive early warnings of extreme trajectories than it would to allow to them to differentiate between rapid and slow rates of change around the median trajectory.

Finally, it should be emphasized that the notion of opportunity cost required to conducted the analysis need not be confined to the benefit side. The cost of any reaction to climate change could easily involve large investments in capital that would otherwise have been devoted to other productive activity. The long term effect of this transfer of investment needs to be considered in situations in which it might be large relative to the economy as a whole; i.e., in evaluating the timing of elaborate adaptive responses in small, developing countries and/or, perhaps, wide arrays of adaptive and averting responses on a global scale. In either case, it may pay to wait so that the present value of the cost of reaction would be smaller for two reasons. First, and most obviously, it would be smaller because the actual expenditure would occur further into the future and would therefore be discounted more severely. Secondly, and more to the point here, it would be smaller because it would be financed out of the resources of an economy which would be larger and more capable of supporting the investment than it otherwise would have been.

What type of information would be most valuable in these cases? Information that would tell if a rapid climate change trajectory were likely so that the potential for large climate change losses prior to reaction could be avoided. Information which differentiated rapid trajectories from the rest would pay off most, and could be supported by vigorous local and regional monitoring of climate variables. Research targeted at resolving uncertainty might also pay off, but it would be most effective if it were directed at quantifying changes in the relative likelihoods of extreme events. The cost deferment of the 'wait and see' mode would therefore not be a prescription for inaction. It would, instead, be a program which relied on information gathering around the extremes to provide an effective level of insurance which could, in other circumstances, be provided by contingent responses and/or early preparation for discrete choices.

IV. Concluding remarks

The problem of analyzing the economic value of potential responses to the effects of global climate change is a problem that lies at the heart of decision making under conditions of enormous long term uncertainty – one of ranking possible responses and evaluating their most advantageous timing on the basis of the current state of our knowledge (or ignorance) of the future. The methodology outlined in Section I is advanced as a first step in confronting that problem, but it contains little new economics. It applies, instead, well established economic tools to provide a means of organizing one's thoughts in face of uncertainty, taking into account not only what we know now, but also what we might know in the future and how we might, in the normal course of events, react to that growing base of knowledge. The responses being considered might not be contingency responses by design, but society will certainty adjust its behavior when it comes to realize that existing pictures of what the future might hold were incorrect.

Only two new wrinkles in existing theory were, in fact, proposed. it was, first of all, noted that the usual representation of uncertainty with subjective distributions of future state variables at some point in time can, in many cases, be replaced profitably in our thinking by the corresponding orthogonal distributions of time when certain specific threshold values in those state variables might be crossed. Many potential responses would be triggered by certain variables crossing such thresholds, so the orthogonal distribution provides a picture of when those responses might be required. In that context, one can investigate the best anticipated timing of some potential response given the current subjective view of the future by taking advantage of the second wrinkle: defining, for each discrete policy option, a set of responses differentiated only by the time in which they would be enacted. The best anticipated response then defines not only the best structural reaction, but also its best anticipated timing.

Application of the methodology also provides some general insight. To the extent that communities can correct any error in anticipating exactly when a given response might be required, new information which can differentiate future states of nature prior to the need to respond will be less or more valuable. That point notwithstanding, however, it is quite possible that the best anticipated response might be guarding against the potential effects of scenarios at the extremes of current subjective distributions even at the risk of being 'overprepared.'

Finally, the notion that societies will learn about the future as it unfolds should also be considered. Again, this sort of learning may generate large or small increases in net expected benefit depending upon its decision makers' abilities to correct for errors in anticipation. Learning can, in any case though, be expected to reduce the variance of possible futures at the time of actually initiating a response. Any degree of risk aversion in the evaluation function will, of course, therefore welcome the opportunity for such learning.

Notes

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2. See Table 2.1 in Schneider and Rosenburg (1989) for a catalog of possible effects, ranges of their potential magnitude, and subjective forecasts of the time that will be required to achieve reasonable consensus.
3. See Lashof and Tirpak (1989), the IPCC Policy Report issued in 1990, or the proceedings of the Second World Climate Conference (1990) for a catalog of many potential responses to climate change.
4. It is important to note (1) that new information is useful only when it becomes available before the need to respond materializes fully and (2) that its value must be evaluated in the context of the world as it will be then and not in the context of the world as it is now. Certain irreversible effects may occur in the meantime, and their implications must be incorporated in any consideration of the value of waiting.
5. The variable y, for example, might reflect the level of the sea in which case θ would include variables like emissions or concentrations of radiatively active gases, the rate of change of global temperature, the rate of heat transfer into the oceans and their various layers, and the rate of thermal expansion of the oceans while γ would include things like tide variability and local weather.
6. See Waggoner (1989) for a lucid analysis of the relationship between mean precipitation (correlated with climate) and associated frequency distributions of monthly precipitation. Special care is taken there to trace the correlation between changes in the mean and changes in the relative likelihood extreme precipitation events on both sides – drought and flood.
7. Even when the cost is driven by the noise, as suggested in the last paragraph, the functional relationship between cost and the long term stochastic variable can be captured by accurately representing the correlation between long term trend and the relative frequencies of the extreme events which produce the cost.
8. Recall Figure 1's display of divergent opinion over future sea level rise. Statistical techniques can be employed to reflect its content in the probabilistic format of Figure 2 and to construct corresponding distributions of sea level intervals for any point in time. See Nordhaus and Yohe (1983) for details.
9. From current perspectives, the major effect of Bayesian Learning is a reduction in the variance of anticipated outcomes. Linear objective functions ignore variance and focus entirely upon mean, and the potential for future learning has no effect on contemporary estimates of the mean.
10. See Nordhaus and Yohe (1983) for a discussion of this technique. It assumes implicitly that every expert estimate is sample point derived from the true distribution; as should be expected, it has been shown, at least in one case, that it tends underestimates true variability [see Yohe (1987)].
11. This is one of a series of arbitrary assumptions that must be made to apply existing data. Future work, using the methodology generated here to define the empirical requirements, will relax these assumptions.
12. These cost estimates were drawn directly from Weggel (1989).
13. The sensitivity of this ranking result to the underlying subjective distribution of sea level rise can be investigated. A mean preserving 50% contraction in the variance of the lognormal distribution of greenhouse induced sea level rise through the year 2100 showed, for example, a small decline in the relative efficacy of planning for a dike in 2015. The dominance of planning for a dike over the continuous response persisted nonetheless.

14. Recall, as well, that these are 'present value dollars.' Potential costs and benefits extending decades into the future were discounted at 3%.
15. Again, the calculation of relative efficiency must be conducted in terms of what the world will be like after a (perhaps prolonged) period of inaction (or alternative action).

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