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INTEGRATED RISK ANALYSIS OF GLOBAL CLIMATE CHANGE

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ABSTRACT

This paper discusses several factors that should be considered in integrated risk analyses of global climate change. We begin by describing how the problem of global climate change can be subdivided into largely independent parts that can be linked together in an analytically tractable fashion. Uncertainty plays a central role in integrated risk analyses of global climate change. Accordingly, we consider various aspects of uncertainty as they relate to the climate change problem. We also consider the impacts of these uncertainties on various risk management issues, such as sequential decision strategies, value of information, and problems of interregional and intergenerational equity.

1. INTRODUCTION

There is a long history of scientific study of global warming. Fourier (1827) may have been the first to notice that the earth is a greenhouse, kept warm by an atmosphere that reduces the loss of infrared radiation. The overriding importance of water vapor as a greenhouse gas was recognized even then. Arrhenius (1896) was the first to quantitatively relate the concentration of carbon dioxide (CO_2) in the atmosphere to global temperature. Scientific understanding has increased since then, particularly stimulated in the latter half of this century by the conclusion of Revelle and Suess (1957) that human emissions of CO_2 would exceed the rate of uptake by natural sources in the near term, and by the demonstration of Keeling *et al.* (1989) that atmospheric CO_2 is steadily increasing. These scientists' warnings had little effect on public opinion and policy until the summer of 1988, at which time it was noted that five out of the previous six summers in the United States were the hottest on record. In addition, the long-term global temperature record was presented to the U.S. Congress suggesting that a global mean warming had emerged above the natural background variation (Hansen 1981).

Most of the warming in this century occurred before 1940, when CO_2 emissions were much lower than they are today. This observation has led some scientists to question the reality, or at least the imminence, of global warming (see, e.g., Seitz 1994 and Figure 8 below). Although the cooling caused by anthropogenic aerosols seems a likely process that has masked the effect of rising CO_2 emissions, the explanations presented to Congress troubled some people. In the policy debates that

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followed, few proponents enunciated clearly how — in their view — society should proceed in the face of uncertainty. Should society ignore global warming (as Seitz seems to suggest) until there is definitive and direct evidence for its occurrence, and for adverse consequences associated with its occurrence? Or, rather, should society argue for action to prevent anthropogenic changes that are comparable to natural disasters, and that might have dramatic effects at a future time when mankind has developed habits that are difficult to reverse? In our view, the difficulty of discussing these matters in a consistent and rational manner has led to polemics. The purpose of this paper is to discuss the manner and degree to which the developed approaches of risk analysis can address the problems.

During the course of the past several decades, the field of risk analysis has emerged as a useful means by which to structure and evaluate complex public policy decisions concerning human health and safety. As commonly construed, the notion of *risk* conjoins two basic ideas, namely, that of *adverse consequences* and that of *uncertainty*. Typically, risk analysts distinguish between *risk assessment*, on the one hand, and *risk management*, on the other. According to this distinction, risk assessment attempts to valuate undesirable outcomes and to assign probabilities to their chance of occurrence, whereas risk management involves political decisions as to what can, or what should, be done to control or otherwise mitigate societal risks.

The adjective *integrated* should hardly be necessary in discussions of risk assessment. Rind *et al.* (1988) and, more recently, Dowlatabadi and Morgan (1993) and Parsons (1994), emphasize its importance in their studies of global climate change. The phrase "integrated assessment" has become fashionable, with many funding agencies now encouraging integrated assessments of global climate change. In our view, an integrated assessment should be done in such a way as to enable all relevant aspects of a problem to be considered simultaneously. That does not mean that every detail should be considered. An important challenge in risk analysis lies in showing linkages between different parts of a particular problem, and finding how they may be decoupled into discrete, separable modules that can receive individual attention. A book on integrated assessment methodology, using the IMAGE model of Rotman (1990), has recently been published by Elzen (1994).

An integrated assessment should also mean more than incorporating all processes into one gigantic model or computer program. Although it is clearly essential to couple the various computer programs that have been written to describe various aspects of the problem, careful thought on how linkages occur and which factors are important is also necessary. To this end, a simple diagram and analytic approach can help ensure that risk managers address appropriate issues and concerns. We believe that comparisons with other risks in society can help to describe and explain this risk.

Crucial, also, to the concept of an integrated risk assessment is the importance of a "model" to link all aspects of the matters of concern. It is, perhaps, a well accepted dictum among scientists and engineers that "all models are wrong, but some models are useful." It follows that it is important to discuss the range of validity of any particular models. Few people believe the detailed risk numbers given by a Probabilistic Risk Analysis (PRA) for a nuclear power plant or the space shuttle. But the *process* and the discussion of its limitations ensure that the technology is understood, and there are no important gaps in safety assessments. By analogy, people might not believe the numbers at the end of an integrated assessment, but by thinking through the process, they can assure themselves that no important processes are left out. The current General Circulation Models (GCMs) are very poor in their detailed regional predictions. This fact may not affect their usefulness for *global* concerns; but, any detailed regional impact assessments should probably only be taken as *indicators* of possible impacts, rather than reliable predictions of the future.

The word "integrated" seems to oppose the emphasis by two committees of the National Academy of Sciences (National Research Council 1983) on separating risk assessment and risk management. This separation was deemed necessary to ensure that scientific data collection and evaluation is not biased by other societal values. Already, several authors have pointed out that this separation can go too far (Wilson and Clark 1991, Valverde 1992). One way that risk assessment and risk management are intertwined is in the understanding of how cautious the decision maker wants to be. Technically speaking, at what point on the probability distribution of the final answer of an assessment should a decision maker take action? It is important that the *assessment* contain enough information for the manager to decide this appropriately.

It is sometimes convenient to distinguish between a *horizontal* integration and a *vertical* integration. In a horizontal integration, all outcomes are considered simultaneously, while in a vertical integration the sequence from cause to outcome is considered. Ideally, a full integration considers all of these facets at once. In this paper we emphasize the vertical integration that we believe is the most important.

This paper lays out several important factors that should be considered in the integrated risk analyses of global climate change. In Section 2, we lay out a simplified progression of cause and effect, showing how the problem can be decoupled into a series of largely independent steps. In Section 3, the issue of uncertainty is discussed, which is a central feature of any analysis of the potential risks of global climate change. Section 4 goes into more detail on each of the steps in the risk layout of Section 2, and further considers the difficulties faced in assigning probabilities to the uncertainties that characterize the global climate change problem. In Section 5, we show how these risks might be compared with other risks in society. Section 6 is devoted to the twin problems of overconfidence and surprise in scientific inference and prediction, as well as the truncation of probability distributions by other (usually historical) data. The remaining sections deal with various limitations of the simple approach presented in Section 1. Section 7 discusses the problem of formulating sequential strategies for making global climate change policy decisions. This is closely coupled with the issue of value of information in global climate change research. Section 8 discusses the balancing of cost-benefit and risk. Lastly, Section 9 discusses how global climate change introduces problems of interregional and intergenerational equity, and how such problems can be formally addressed in risk management decisions.

2. ANALYZING THE RISKS OF GLOBAL CLIMATE CHANGE

Integrated risk analyses of global climate change seek to arrive at answers to the following basic question: *What are the likely impacts of global warming upon the world, and can the possible adverse impacts be eliminated or reduced?*

There are various recommended procedures for carrying out formal risk assessments. The most generally accepted one is that of the National Research Council (1983), which was developed specifically to analyze the risks of chemical carcinogens. A more general approach was put forth by Crouch and Wilson (1981). For the *assessment* of the potential risks of global warming, we use a general layout of the progression of the physical processes involved. This general layout is stimulated by ideas originally put forth by Kates *et al.* (1985). We divide the processes leading to global warming into a sequence of roughly independent steps. Our diagram is simplified by considering only CO_2 as a greenhouse gas. This simplification is made because CO_2 is the most important greenhouse gas that humans can alter. A more complete diagram would show other entries, such as methane, nitrous oxide, and chlorinated fluorocarbons. The difficult scientific question of the role of water vapor, the most important greenhouse gas, is discussed later in this paper.

For clarity, we enumerate the steps of the main sequence running from top to bottom in the center of Figure 1 by the numbers 1–6 referred to in the text. Equation (1) below represents the final environmental outcome of interest as the product of six factors corresponding to these steps. The first factor is the world population; the second factor is energy production *per capita*; the third factor is the total CO_2 emissions per unit of energy production; the fourth factor is the increase of atmospheric concentration of CO_2 per unit emission; the fifth factor is the temperature rise per unit of CO_2 concentration; the sixth factor is the environmental outcome of interest (e.g., sea level rise) per unit temperature rise.

$$\Delta h = \overset{1}{population} \cdot \overset{2}{\left(\frac{energy}{person}\right)} \cdot \overset{3}{\left(\frac{CO2_{emit}}{energy}\right)} \cdot \overset{4}{\left(\frac{CO2_{atmos}}{CO2_{emit}}\right)} \cdot \overset{5}{\left(\frac{\Delta T}{CO2_{atmos}}\right)} \cdot \overset{6}{\left(\frac{\Delta h}{\Delta T}\right)} \qquad (1)$$

The relationship of Equation (1) to Figure 1 is explained as follows: the product of the first two factors is the world energy use; the product of the factors 1, 2, and 3 is the total of world CO_2 emissions; the product of factors 1– 4 is CO_2 concentration, and so on.

All calculations of global warming that we have seen follow this layout and formula to some extent, although some ask more limited questions, and therefore follow only a part of the procedure. For example, the report from Working Group III of the Intergovernmental Panel for Climate Change (IPCC) (Bernthal 1990) discusses various energy scenarios for the world.

This encompasses Factors 1, 2, and 3. Factor 4 comes from scientific discussions of the fate of CO_2 in the environment. The output of General Circulation Models (GCMs) is represented by Factor 5, and it is here that the main scientific controversy lies. The report of the IPCC Working Group I (Houghton *et al.* 1990) describes Factors 4, 5, and 6, whereas Working Group II (Tegart *et al.* 1990) was concerned with various impacts of global change, and therefore addressed Factor 6.

In writing Equation (1), we assume that each factor is independent of all the others. Indeed, the factors are chosen so that this is approximately true. This is a simplifying assumption that enables us to make a first approximation to the environmental outcome(s) of interest. Further refinements would be to identify, for example, those environmental outcomes that arise from correlations that exist between the factors — such as the combined effects of CO_2 and temperature on plant growth.

Further, as discussed below, Equation 1 is a *static* representation of the problem. Of course, in reality, the physical situation evolves with time. This means that when the CO_2 concentrations have reached double pre-industrial levels, the temperature rise will not have reached the value given by the static calculation. Missing in this static representation are the effects of large heat sinks. These simplifications notwithstanding, Equation 1 is a useful preliminary framework to discuss the uncertainties that arise from an incomplete understanding of the physical processes. We note that the Environmental Protection Agency, in a characterization of several models, has also used a factorization such as this.

Note that Equation (1) is written in such a way that the units are automatically correct. It should be evident that the diagram (and the equation) should branch just before Factor 6, which allows for different possible outcomes. Alternatively, several diagrams may be discussed, and the overall outcomes related to each other (perhaps by cost per unit outcome) and summed. Later in this paper, we discuss the work of Oerlemans (1989) on possible sea level rise. Historically, sea level rise has been the parameter that has most attracted people's imagination, although the effects of climate change on agriculture may be the most important outcomes (Bowes 1993, Crosson 1993).

Each factor in Figure 1 and in Equation (1) has both recognized and unrecognized or unsuspected uncertainties. An important issue is what these uncertainties are, and how to combine them to give the *overall*, or total, uncertainty in the final outcome. This issue is discussed further in Section 3.

We agree with the National Research Council (1983) that risk assessment should be independent of the management decisions that follow it. In general, the assessor should restrict his advice to giving alternatives from which to choose for the risk manager. Once presented with the estimated

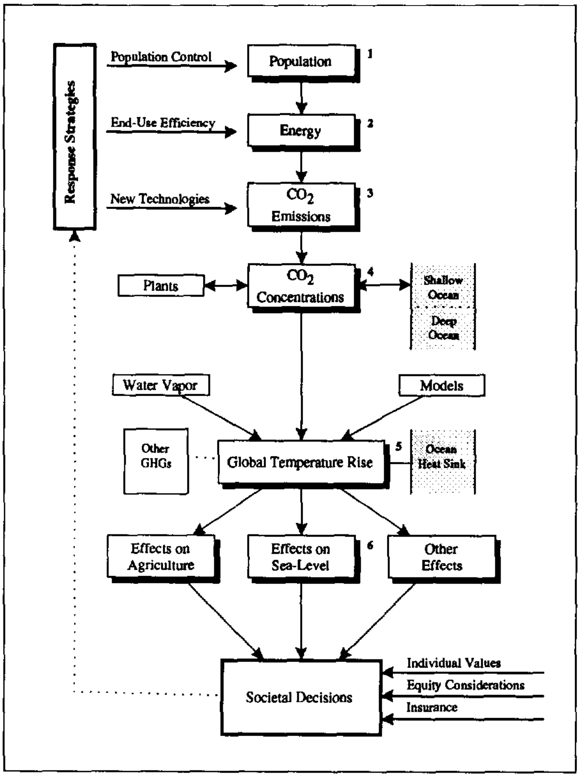

Figure 1. The proposed causal framework for global climate change consists of three parts: climate change assessment, impact assessment, and risk management. Population and energy policy studies together with models of the climate system serve as inputs to climate change assessments. Impact assessment is concerned with the effects of climate change. World population, energy consumption, and CO_2 emissions appear as endpoints in risk management decisions about climatic change.

outcome, along with its uncertainties, a risk manager or managers must decide what, if anything, to do. But, as noted above, he should try to understand the limitations of the information presented to him, and it is in this understanding that we believe that papers such as this can be of help. The options for action are limited, and are illustrated on the left side of Figure 1.

At the top of Figure 1 is a line suggesting that we can modify world population (e.g., upward by reducing war, famine, and pestilence; downward by birth control) by societal action. The next line suggests that humans may modify the energy use per capita (e.g. upward by increasing the global standard of living, or downward by increased efficiency of energy use). The third line suggests that we can modify CO_2 emissions per unit of energy (e.g., upward by abandoning nuclear energy, or downward by replacing fossil fuels — especially coal — by alternative fuels, such as nuclear, hydro, and solar).

Although it is intuitively attractive to create a sink for CO_2, we do *not* draw a line in Figure 1 to modify the ratio of concentrations to emissions, because, at this time, the scientific consensus seems to be that this is not possible on the necessary scale. Nor do we draw a line suggesting a modification of the ratio of temperature rise to CO_2 concentration, in that we know of no suggestion that this can be done. We do, however, draw a line suggesting a possible mitigation of the outcome given a temperature rise. If the outcome is defined generally (e.g., the effect on GNP), humans can modify this factor by *adaption* — such as moving north as the temperature goes up.

3. ADDRESSING UNCERTAINTY

As noted above, each one of the factors in Equation (1) and in Figure 1 is uncertain. In this paper, we distinguish between different *types* of uncertainty. To illustrate this point, we draw upon experience from two other fields: (1) the study of safety of nuclear power stations or of chemical manufacturing plants; and (2) calculations of the risks of chemical carcinogens.

In a discussion of the risks of chemical carcinogens, Wilson, Crouch, and Zeise (1985) distinguished between *stochastic uncertainties* and *uncertainties of fact*. The statement that a cancer risk is 10^{-6} per life means that an individual is unlikely to develop cancer from a given exposure to a particular chemical, but that one person in a million will. Thus, there is a "stochastic uncertainty" for a given individual. A different type of uncertainty is the uncertainty of the slope of a dose-response curve, which gives the projected number of cancers per unit exposure. As typically construed, this slope — regardless of its value — is the same for all exposed individuals. This type of uncertainty is sometimes referred to as "uncertainty of fact," thus distinguishing it from stochastic uncertainty.

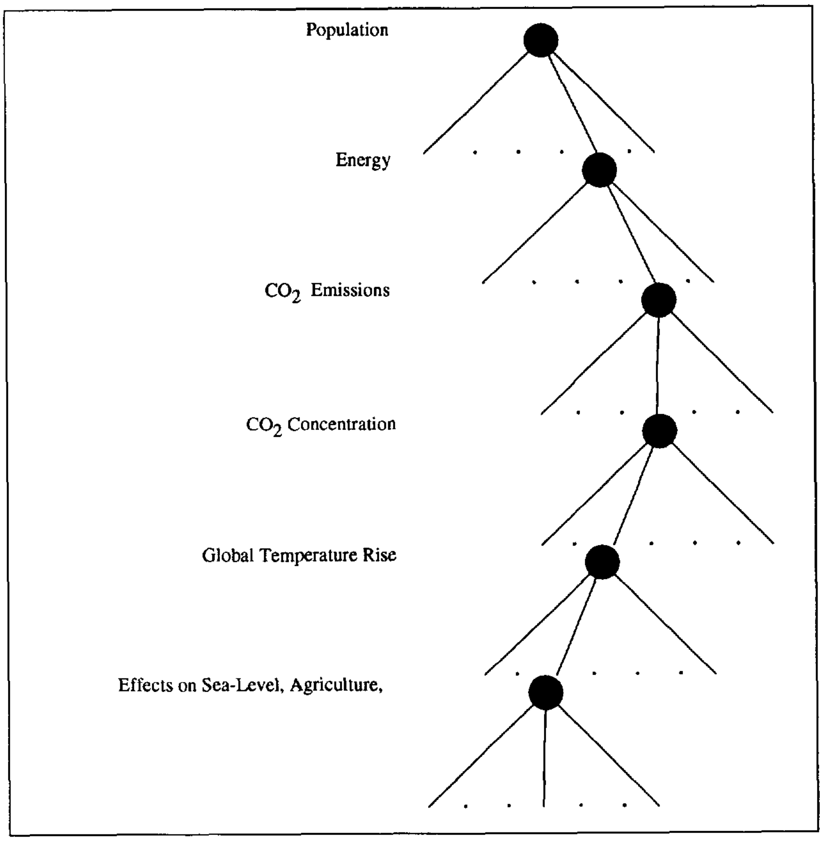

Figure 2. Cascading of uncertainties.

The uncertainties that characterize the global climate change problem are both factual and stochastic in character. For example, the scatter of predictions for the sensitivity of climate system to CO_2 doubling is, in some ways, analogous to the uncertainty of the slope of a dose-response curve. Stochastic uncertainty arises at the end of the causal chain; without detailed information concerning regional impacts, it appears to be almost random how changes in CO_2 would affect a particular community.

Further, it is clear that the uncertainties in the first few factors are different still. They are largely uncertainties concerning what society will do in response to the global climate change problem. Although these uncertainties can often be addressed by examining past experience, people have a habit of surprising analysts. Indeed, one of the purposes of analyzing the risks of global warming is to encourage people to behave in productive ways that are *not* predictable from past behavior.

Combining uncertainties in several factors is straightforward when these factors are independent. The effects of correlations between variables can often be ignored, particularly if the correlation coefficients or the uncertainties in the correlated variables are small. Also, if the risk model includes both correlated and uncorrelated uncertain inputs, the uncorrelated inputs will moderate the effect of neglecting correlation (Smith *et al.* 1992). For simplicity, we neglect possible correlations between the different factors in Equation (1).

Schneider (1983) suggests that uncertainties should be combined by considering each component of the overall CO_2 problem as part of a cascading pyramid of uncertainties. Using the elements of Figure 1, Figure 2 illustrates one possible framework for this. Specifically, the figure illustrates how a probability tree for the first six elements of the global climate change problem presented in Figure 1 and in Equation (1) might look like. For each factor, there is, of course, an infinite number of possible values.

For each vertex in Figure 2, we show three choices: low, medium, and high. This means that there are $3^6 = 729$ possible scenarios. In order to completely analyze even this simplified diagram one would have to evaluate each of the 729 scenarios. Naturally, this is a formidable task, which no one has undertaken. Instead, most assessors of global warming evaluate the uncertainties by considering a continuum of choices for each factor, governed by a probability distribution. Following this line of reasoning, we suggest that the three values chosen for each factor in Figure 2 be the median and two extreme points of a distribution, one on each side of the mean. A similar distributional approach has been developed by Evans *et al.* (1994) for chemical carcinogens.

Again, *assuming independence of each factor*, the probability distributions can now be combined. This is particularly simple if each distribution can be treated as approximately lognormal. In such instances, the final distribution is lognormal with the logarithmic standard deviation given by the square root of the sum of squares of the individual geometric standard deviations. If the distributions are far from lognormal, Monte Carlo methods can be used to combine them.

Mathematically, this particular method of combining the distributions is similar to the event tree procedure developed by Rasmussen for calculating the probability of a nuclear reactor accident (Atomic Energy Commission 1975). In assessing the risks to human health and safety posed by complex technical systems, it is recognized that the failures of components can be treated in a statistical fashion; if it is assumed that these events are mutually independent of each other, then the probability of a major accident can be estimated. The event tree procedure is more general, in that each scenario can be assigned a weight. The problem becomes much simpler if we assume independence of the probabilities at each node, and, as mentioned above, simpler still if we are able to approximate the probability distribution at each node by a lognormal distribution. The Rasmussen report was originally criticized because the probabilities at each event vertex are not always independent of each other. An important challenge in the construction of event trees is to choose trees where the vertices are *almost* independent. Under such conditions, the residual dependencies stand out, and can be more readily recognized and calculated.

This procedure is also analogous to the procedure for calculating the risk of exposure to chemical carcinogens. In such analyses, carcinogenic potency is measured in animals with some uncertainty, then an uncertain interspecies conversion factor is used to predict carcinogenicity in humans. The final uncertain factor is the dose to which humans are exposed. Crouch and Wilson (1981) and Wilson, Crouch, and Zeise (1985) point out that these three factors are approximately independent of each other, and they approximate them by lognormal distributions, which are then combined analytically. Recently, analysts of chemical risks have tended to fold these distributions by Monte Carlo calculations, even though independence is typically assumed (Finley and Paustenbach 1994).

In the United States, the approach that most regulatory bodies take towards uncertainty is very conservative, and does not always take into account the best analytical methods that may be available. The EPA's approach to uncertainty propagation, for example, takes a conservative upper limit for each risk factor. The upper limits are then multiplied to arrive at a total risk level for regulation. Regardless of whether this procedure is used for final regulation, it obscures understanding of the problem, in that it gives too little information to the risk manager.

4. DISCUSSION OF THE INDIVIDUAL FACTORS

We now consider in detail each of the factors in Figure 1 and in Equation (1).

Factor 1: Population

In making decisions about global climate change, we may endeavor to reduce world population. Discussion of this topic dates back at least to Malthus' (1798) famous essay on population. Malthus suggested that unless society took an orderly action to reduce population, then war, famine and pestilence would take their toll. Indeed, in the 1990s, civil wars in Bosnia and Rwanda are reducing the population, but not (yet) on a global scale. Pestilence may also be important, as the unchecked ravages of AIDS in Africa suggest. But, these examples all have a common feature: mankind is doing its best to stop many processes that would otherwise reduce the population. Positive steps to reduce population are being taken in many countries, China perhaps being the most successful.

Population studies is a fairly mature science, and predictions of world population over the next few decades have smaller relative uncertainty than estimates of some of the other factors in Equation (1), such as sea-level rise per unit warming. Although Shlyakhter and Kammen (1993a) have shown that forecasters often underestimate uncertainties in their projections (see Section 6), even the (larger) true uncertainty in population projection has little effect on the total uncertainty in the outcome. Therefore, calls for reducing world population are unlikely to have much effect on global warming in the next century.

Factor 2: Energy per person

Energy use *per capita* has been discussed by Hafele *et al.* (1981) and by Goldemberg *et al.* (1988). The most effective way to reduce energy consumption is through improving end-use efficiency (Goldemberg *et al.* 1988). Hafele *et al.* point out that as countries develop, the energy use per capita increases sharply, and even the energy use per unit of GNP rises. Such effects are often associated with the migration of population from the countryside to the towns. But later in the development process, energy use per unit of GNP falls. This decrease comes about for various reasons. After a country passes a threshold of energy use, and a technological foundation is established for a new technology, further increases of GNP are inherently less energy intensive. Naturally, this observation raises the question of how efforts to improve energy efficiency in developing countries can accelerate this historical process.

Economists argue — with considerable historical justification — that the most effective way of encouraging energy efficiency is by increasing the price of energy. The use of taxes or charges to reduce energy use per capita has been discussed by Nordhaus and Yohe (1983), Nordhaus (1991), and by Jorgenson and Wilcoxen (1991). Wilson (1989) has noted how energy efficiency improvements seem to correlate with oil price changes. This correlation suggests that an important way of reducing CO_2 emissions is by raising the price of fuels. In 1993, the U.S. people, through its representatives in Congress, rejected a "carbon tax" that might have achieved this goal. Therefore, searches must continue for other methods of stimulating efficiency, even if less effective.

In light of the U.S. rejection of a carbon tax, and other rejections of price increases, considerable attention has been paid to alternative methods of encouraging efficiency - either by providing information, or sometimes, by compulsion. Mandatory automobile efficiency standards in the U.S. *compulsion* have improved efficiency. However, there were price fluctuations and small tax increases in this period, and it remains a matter of debate exactly which effect caused the increase in efficiency. While price may have been a factor in the increase in efficiency, gasoline has been a diminishing factor in the cost of running an automobile over the last 40 years, and the price normalized to the cost of living index has fallen in the same period. In this light, we believe that the U.S. Congress' technology forcing approach was the principal cause of the efficiency improvement.

Many authors (see, e.g., Wilson 1989) have pointed out that energy efficiency can also be achieved by improving the flow of information to consumers, and by reduction or removal of perverse counterincentives. Among these, the practice that is common in offices and institutions of charging electricity and heat to its members and employees to "overhead," and therefore making the individual consider it as a free good, is endemic. The labelling law for appliances is a good example of the effect of good information. But, neither the provision of information or the removal of perverse incentives are likely to work unless the price is already high enough to provide an incentive for change (although a changing price is not necessary).

Factor 3: CO_2 emissions per unit of energy

The amount of CO_2 emitted per unit of energy produced is not constant, and can be changed by societal action. Some sources of energy (e.g., hydro, solar, and nuclear) produce none. Fossil fuels differ in the amount of CO_2 emissions per unit energy. The energy from coal comes solely from the conversion of carbon to carbon dioxide, whereas when natural gas (CH_4) burns, both carbon and hydrogen contribute. Combustion of natural gas produces half the amount of CO_2 produced by the combustion of coal. In addition, natural gas is easier to use, so that 52% thermodynamic efficiency has been achieved in a combined cycle turbine vs. 42% for the best coal burners. But, all of this gain can all be lost if *any* natural gas leaks anywhere in the cycle — from the well to the burner — because CH_4 is a greenhouse gas that can be dozens of times as important as CO_2 (Shine *et al.* 1990). A few percent leak in the system leads to a *doubling* of the greenhouse effect, and negates the advantage over coal. There seems to be a wide geographic variation in such leaks, or at least a difference of opinion about their importance. Leak rates of 15% have been suggested for the Siberian pipeline, and elsewhere, 10% leaks have been suggested (Grubb 1991). However, others claim that leak rates in the whole system for electricity generation in the U.S. are less than 0.1%. This is clearly a topic that can be elucidated by further study, and the effect can possibly be reduced by further action.

Nuclear energy expanded rapidly in the late 1970s, but at about 1980, the expansion slowed, and *no* new nuclear power plants (that were not subsequently canceled) have been ordered in the United States since 1977 . Yet, enough coal-fired power plants were built in the U.S. since 1975 to increase U.S. CO_2 emissions by five percent (Boden *et. al.*, 1990). This observation suggests that utility decision makers *have not* put the possibility of global warming high in their considerations of what power plants to build. Nor does the record show that it was a consideration in the recent decisions to close the San Onofre and Trojan nuclear power plants and to replace them by natural gas power plants (Wilson 1994). This may change if and when public utility commissions demand that "externality" values be attached to CO_2 emissions by power plants (including all aspects of their fuel cycle).

The U.S. and Europe have already installed hydroelectric plants in most reasonable sites, but China and Africa may have more development opportunities. Although there has been considerable political support in the last twenty years for expanding various forms of solar energy, this has not happened on a large enough scale to affect CO_2 emissions. It is possible that many of the constraints affecting nuclear power (such as difficulties in getting a new technology into effective use) also affect solar energy. For example, it is of interest whether the natural progression of energy use in developing countries outlined by Hafele *et al.* (1981) can be altered by help from developed countries. Assistance in developing solar ovens and windmills in Kenya (Kammen 1992), or in developing nuclear power in Asia can be useful steps in reducing CO_2 emissions. Wilson (1989), Starr (1990), and Bodansky (1991) have all pointed out that for electric power, improvements in end-use efficiency (leading to a reduction in Factor 2) and a choice of the generating source are almost independent societal decisions. An important exception, of course, is the use of cogeneration — producing electricity and heat at the same time. The flexibility of the use of natural gas makes cogeneration much easier if natural gas is used as the fuel rather than coal.

Factor 4: Fraction of the emitted CO_2 that stays in the atmosphere

Keeling *et al.* (1989) have measured CO_2 concentrations over many years. If one naively assumed that all of the CO_2 emitted from fossil fuel burning stays in the atmosphere, then the CO_2 concentrations would be increasing at twice the rate that has been observed. This leads to a discussion of the *carbon cycle*, or carbon budget (Revelle and Seuss 1957, Revelle and Munk 1977, Bacastow and Keeling 1981, Moore and Bolin 1986, Keeling, Bacastow and Carter 1989, Siegenthaler and Joos 1992, Moore and Branwell 1994).

Thus, a critical scientific uncertainty is the environmental sinks for CO_2. Terrestrial plants and soils are both potential sinks, and the oceans are another. Although the deep oceans are effectively unlimited in the amount of carbon they can absorb, the rate of absorption is limited by chemical partitioning rates, as well as the transfer rates between the surface water layers and the deep oceans. Sophisticated models use a number of time constants to describe this process, and use a number of terms to describe the most important aspects. Bacastow and Keeling (1981) defined the "airborne fraction" as the ratio of the increase in atmospheric CO_2 to the amount of CO_2 emitted by human activity during a given period. The "atmospheric residence time" is the ratio of the quantity of CO_2 in the atmosphere to the flux out of the reservoir to the land and soils. More important for the policy analyst, however, is the "readjustment time" which describes how the system might return to equilibrium after human emissions cease. The initial readjustment would be to the land and to the shallow oceans, which have a time of perhaps 30 years; later readjustment probably involves mixing of the shallow and deep layers of the oceans, and may be 200 years.

In 1977, one school of thought held that the characteristic time for mixing of the deep and shallow oceans was closer to 800 years, and this dominated the time for the concentration to come to equilibrium. Most experts now put that estimate at 200 years or less. Lindzen (1991, private communication) and Heimann (1991) have even suggested that the "effective" time constant for carbon absorption by the ocean and the biosphere may be on the order of that for the exponential increase of emissions, i.e., approximately 50 years. Although this is a minority view among climate scientists, the crucial question remains: *what will be the future CO_2 concentrations if we succeed in limiting the increase in emissions?* The answer to this question depends critically upon these time constants. Optimists argue that the effect of any effort to reduce emissions will result in limiting the duration of high concentration — and therefore temperature increases — to 50 years or less. Pessimists, on the other hand, argue that the actual time constant is 800 years, and even if intervention reduces anthropogenic CO_2 emissions to zero, high concentrations will persist for 800 years. Any analysis incorporating uncertainties should presumably take into account this range of possibilities.

In view of the recent realization of the importance of sulfate and other aerosols as contributors to "global cooling," it is important to realize that the residence time for these aerosols is much shorter — on the order of days or weeks rather than years — since aerosols wash out with rainfall.

Factor 5: Global temperature rise per unit increase in atmospheric CO_2

The central issue of the scientific debate on global warming is the temperature rise resulting from an increase in the atmospheric concentration of greenhouse gases. These greenhouse gases include — in addition to carbon dioxide (CO_2) — methane (CH_4), nitrous oxide (N_2O), freon, and, most importantly, water vapor. Factors that determine concentrations of these greenhouse gases (except water vapor) from known emissions are moderately well understood. Global temperature rise does not directly affect the atmospheric concentrations of these gases. But, as anyone can see by observing the earth's clouds, the concentration of water vapor varies rapidly in space and time, and this variation arises from feedback mechanisms that are less well understood.

Shine *et al.* (1990) developed the concept of Global Warming Potentials (GWPs), which compares the relative effects of different greenhouse gases in absorbing the infrared radiation emitted by the Earth. The concept of GWPs was intended as a guide to policy makers in making trade offs between reducing (or increasing) one gas instead of another. While it might be a useful concept, there are ambiguities in the derivation and use of GWPs, the reason being that molecular absorption bands can overlap. Should one consider the absorption effect of CO_2 in an atmosphere *without* water vapor, or with a typical concentration of water vapor? Moreover, the GWPs can vary with concentration, since the effects can be nonlinear. More important, perhaps, is the absence of a clear policy decision about where these tradeoffs are important.

A key scientific uncertainty in the global climate change problem lies in evaluating climate sensitivity, i.e., the global temperature rise per unit increase in atmospheric CO_2 concentration. Climate sensitivity is estimated on the basis of General Circulation Models (GCMs), which calculate the global mean temperature increase from an increase in CO_2 concentrations that is maintained at a constant level over a long period of time (Houghton *et al.* 1990, NAS 1991). This is sometimes called an *equilibrium response* to a static, or quasi-static, doubling of CO_2. In reality, this process is *dynamic* in character, with CO_2 concentration rising steadily. The temperature rise does not follow immediately after a rise in CO_2 concentration, but rather lags, due to the coupling of various heat sinks. Nevertheless, it is useful to consider first the simpler problem of estimating the temperature rise that would result from an equilibrium situation after CO_2 has doubled, or after all emitted gases have produced an equivalent radiative absorption. The lag of temperature rise is large enough that, at the time that CO_2 doubling is reached, only a 0.5°C - 1.0°C temperature rise is expected, not the equilibrium temperature of 2.5°C (Cubasch and Cess 1990).

If there were no change in the concentration of water vapor (such as would be the case if the Earth were completely dry), the global-mean surface temperature would increase by $\Delta T_d = 1.2°C$, given a static doubling of CO_2. This estimate also depends on the assumption that the cooling of the Earth is from the stratosphere, and that there is a fixed air temperature distribution with height. But, concentration of water vapor is expected to increase with increasing temperature as water evaporates, and since water vapor is the most important greenhouse gas, this could amplify warming. Water can introduce interactive feedbacks in numerous ways, such as water vapor, clouds (especially cirrus clouds) and snow-ice albedo. These feedbacks introduce considerable uncertainties into the estimates of the mean surface temperature rise, ΔT_s.

The value of ΔT_s is roughly related to ΔT_d by the formula $\Delta T_s = \Delta T_d / (1-f)$, where f denotes the sum of all feedbacks. The water vapor feedback is relatively simple: warmer atmosphere contains more water vapor, which is itself a greenhouse gas. This process gives rise to a positive feedback, in that an increase in one greenhouse gas, CO_2, induces an increase in another greenhouse gas, namely, water vapor. Cloud feedback, however, is harder to evaluate because it depends on the difference between the warming caused by the reduced emission of infrared radiation from the Earth into outer space and the cooling through reduced absorption of solar radiation. The net effect is determined by the amount of clouds, their altitude, and their water content. The values of ΔT_s from different models vary from $\Delta T_s=1.9°C$ to $\Delta T_s=5.2°C$ (Cubasch and Cess 1990). This change wide range is brought about by including one large contribution from water vapor. Typical values for the equation relating ΔT_s to ΔT_d are $\Delta T_d = 1.2°C$ and $f= 0.7$, so that $\Delta T_s = 4°C$. It is important to recognize that some feedbacks of water vapor may not have yet been identified.

It is worth noting that two models which give similar ΔT_s values can differ in the effects of various feedback mechanisms. For example, two GCM models (GFDL and GISS) show an unequal temperature increase as clouds are included (from 1.7°C and 2.0°C to 2.0°C and 3.2°C, respectively). The effects of ice albedo in these two models are different, but opposite, so that the results converge (4.0°C versus 4.2°C, respectively). What this example shows is that agreement between models may be spurious, and both could be wrong. In addition, most experts believe that *f* is high enough (0.7) that even small increases in the value of *f* could result in a runaway warming not estimated by any of the models, leading, ultimately, to a different stable (or quasi-stable) state of Earth's climate (Manabe and Stouffer 1993, Stone 1993, Stouffer *et al.* 1994).

The outputs of the models used by the IPCC (Houghton *et al.* 1990) and the NAS (1991) were given as "bounds" on the global temperature rise ΔT_s. The committee of the National Academy of Sciences explicitly declined to fit a distribution because that might be taken too seriously by policy makers. In Figure 3, we go further than the NAS committee by considering these bounds as extreme values of a probability distribution of global temperature rise ΔT. We assume that the parameter *f* has a normal (or a lognormal) distribution, and adjust the parameters so that the "limits" of IPCC or NAS correspond to upper and lower 95th percentiles of the distribution of *f*. This procedure gives rise to a long tail, particularly to the upper portion of the distribution. It is this tail, and this simple approach, that leads to statements, such as those made by Dickinson (1986), that there is a one percent chance of ΔT being above 5°C for a static CO_2 doubling. We discuss the possible meaning of this claim below.

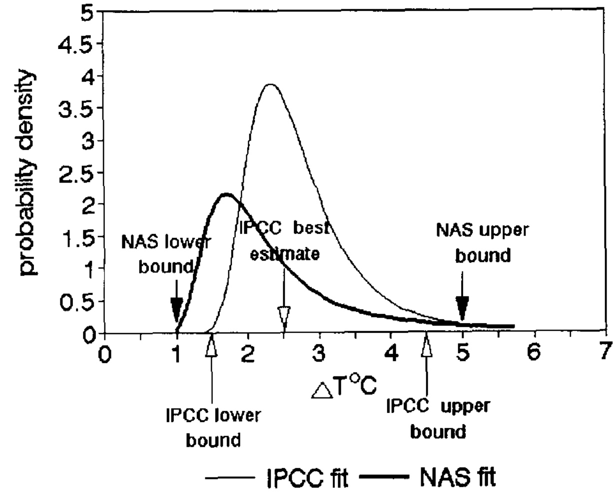

Figure 3. Normal fits to the range of the sum of feedbacks, *f*, corresponding to ΔT for static doubling of CO_2 [data from Cubasch and Cess (1990) and NAS (1991)].

In our framework, the probability distributions associated with the different factors in Equation (1) serve the limited purpose of producing an overall estimate of uncertainty. In using Equation 1, it is important to recognize that the probabilities given here include no contribution from the probability that our understanding of the climate system is fundamentally incomplete. We also note that the bounds given by IPCC and NAS are not rigorously derived from mathematical models, but rather, represent the expert judgement of the committee members of the respective committees. It must be stressed, however, that this was *not* a formally conducted expert opinion survey.

Factor 6: Sea-level rise per unit rise in global temperature

The present best estimate for sea level rise in the IPCC "Business-as-Usual" scenario is 66 cm by the year 2100, and the estimate is based upon the work of Oerlemans (1989), who calculated sea-level rise $\Delta h/\Delta T$ using a simple fit to the temperature rise predicated by a specific global emissions scenario (Houghton *et al.* 1990). This model assumes a simple extrapolation from past behavior for emission of CO_2. Letting $\Delta T = \alpha(t - 1850)^3$, where t is time, we have that $\alpha = 27 \times 10^{-8}$ °K yr^{-3}, and the uncertainty Δ is 35% of the mean for each variable. In terms of Figure 2, Oerlemans started at the fifth level of the tree (from the top). He used the right branch to describe the CO_2 emissions (Business-as-Usual scenario) and the middle (best estimate) values for the subsequent levels of the tree.

Oerlemans (1989) evaluated the uncertainty Δ in the calculated sea-level rise by combining in quadrature the uncertainties in each of the five factors: $\Delta^2 = \Delta^2_{glac} + \Delta^2_{ant} + \Delta^2_{green} + \Delta^2_{wais} + \Delta^2_{expa}$ + *internal variability*. The subscripts refer, respectively, to the effect of glaciers, the Antarctic, Greenland and West Antarctic ice sheets, and thermal expansion of sea water. We are dubious about Oerlemans' assumption of the independence of these factors, so the uncertainty in sea level rise might, in fact, be greater than he calculates. Moreover, in Section 6, we address the possible effects of overconfidence in such predictions. Uncertainty in $\Delta h/\Delta T$ is greater than all other uncertainties about sea level rise, and Δh might even be negative. The magnitude of sea-level rise suggested by Oerlemans is, however, far less than the extremes suggested two decades ago.

The task of combining uncertainties can be simplified when the uncertainties are very different in size. For example, the distribution of predictions of 21 General Circulation Models shown in Figure 7 below has a mean of 3.7°C and a standard error 0.9°C. Given these values, the relative uncertainty is about 0.24, and it contributes just 0.06 when added in quadrature to the relative uncertainty in the sea-level rise, which is close to one. If the relative uncertainties in population projections and energy consumption per capita are on the order of 30%, then their contribution in quadrature to the total relative uncertainty will just increase the relative uncertainty in the sea-level rise from 100% to 125%.

We focus here on sea-level rise because it represents the most dramatic potential effect of global warming, and because it is the effect that has been most extensively studied. Of course, other possible physical effects, such as changes in ocean current systems and Earth's wind patterns, may have more serious and costly effects on, e.g., agriculture and ecosystems. This observation notwithstanding, we must also include the possibility that the effects on agriculture are beneficial for some regions — such as Siberia.

Although we assume independence for each of the factors in Equation (1), the physical stresses that global climate change places on the environment have the potential to compound synergistically. It has been suggested that if surface temperatures increase but temperatures in the troposphere do not, then the strength of storms would (contrary to model predictions) increase (Emanuel 1987). In addition, the reach and severity of storms may be increased by a rising sea level. As alluded to above, ecosystems are also at risk. For example, Bazzaz (1990) and Bazzaz and Fajer (1992) have studied the combined effects of rising concentrations of CO_2, rising temperatures, and increased ultraviolet radiation on plants and ecosystems. Their findings suggest that these factors can give some species distinct advantages over others. For instance, most weeds are more resilient to stresses than are cultivated plants. One possible remedy would be to increase the production of pesticides. Such action, however, would likely lead to increased energy use and potential health risks.

These synergistic effects of temperature rise and CO_2 concentration increase do not invalidate the concept of calculations derived using the assumption of independence, but they do form an exception that must be evaluated separately. This situation is analogous to the deviations from independence in reactor safety calculations due to common mode failures. Rasmussen set up a procedure for analyzing nuclear reactor accidents by constructing an *event tree* that follows the progression of a nuclear power accident from the initiating event to the ultimate consequence (Atomic Energy Commission 1975). The probability of failure was calculated at each step, and it was assumed that each step is independent of the previous one. However, sometimes several events occur simultaneously or several pieces of equipment fail simultaneously. The overall usefulness of the procedure (now called Probabilistic Risk Assessment or PRA) is not invalidated by the existence of *common mode failures*; on the contrary, the procedure has proven to be an excellent means by which to uncover these common modes.

5. CONCEPT OF ACCEPTABLE RISK

Before proceeding further in our discussion of the various issues raised in Sections 1, 2, and 3, we make a comparison with various other societal hazards. This comparison, if done in a reasonable fashion, can aid risk managers in their decision making. However, the comparison should, in our view, be used primarily to ask questions of society and its decision-makers. In a comprehensive and well-publicized study, a team of 75 experts assembled by the United States Environmental Protection Agency compared the potential impacts of 31 environmental problems on economic welfare, human health, and ecosystems (EPA 1987, 1990). Four types of risk were considered in this study: cancer risks, non-cancer health risks, ecological risks, and welfare risks. The study made no attempt to combine expert rankings across these various risk types. Figure 4 illustrates the relative ranking of the six aggregated hazards in terms of their potential impact on welfare and on ecological systems. We note that, in the view of EPA, these risks differ enough in their magnitude that a logarithmic scale is necessary to get the risks on the same graph. Climate change, together with ozone depletion, give rise to the highest expectedecological impacts, but have only a moderate economic impact. On the other hand, the expected ecological impacts of air and water pollution are moderate, while the expected welfare effects are high.

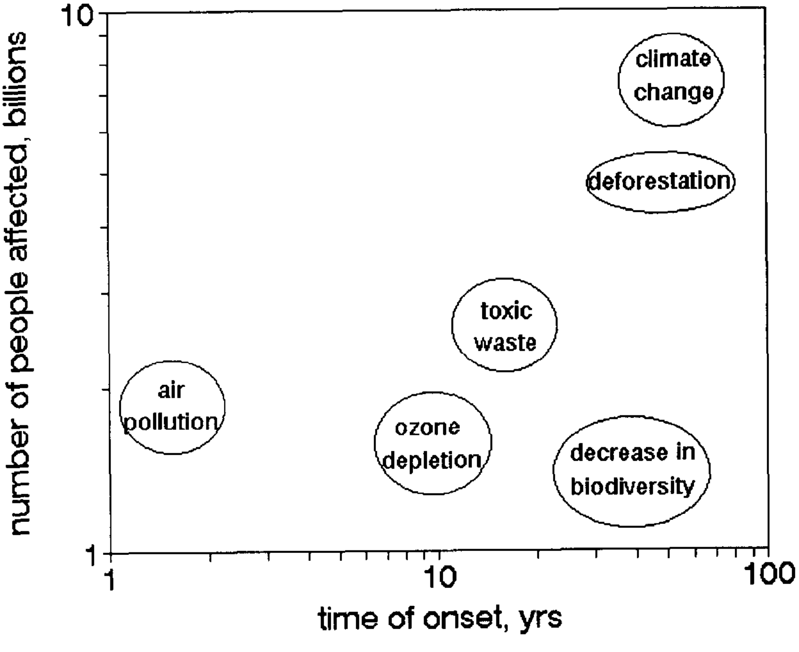

Figure 4. Ranking of environmental risks (EPA 1987, 1990).

Once an assessment of the probability distribution of possible outcomes as been made, it must be communicated to the decision makers in question. What form this information should take, however, is a matter of some debate. For example, it remains an open question whether policy makers are best served by "best guess" scenarios for population growth, energy production, and temperature increase, by a discussion of "upper limits," or by probability distributions of these estimates from which either the best estimate or an upper limit can be derived. In this paper, we advocate the latter approach. It has been frequently noted that different types of decisions require different degrees of caution. More formally, acceptable risk levels are set at different percentiles of the final probability distribution of outcomes. Policy analysts and decision-makers can then draw distinctions between those scenarios that are *probable* and those that are *possible* but extremely unlikely. Those risks that fall below a particular *threshold* of probability — and are thereby ignored by a particular group or society — are called *de minimis* risks. How societies and governments *decide* what constitutes *de minimis* risk in particular situations or contexts is largely a matter of political judgement. For our purposes here, this problem becomes a matter of answering the question, "How improbable is improbable enough?"

In addressing the question, "How improbable is improbable enough?" we pose a more specific question, namely, "At what probability of a serious effect should society take action?" Is there, in other words, a *de minimis* level of risk? Although there is no clear definition of *de minimis* risk, it can generally be seen to be closely akin to a related concept — the *probability of surprise*. Although many conceptions and definitions are possible, our use of the word "surprise" is meant to denote those situations where the true values of a particular uncertain parameter, e.g., the slope of a dose-response curve, climate sensitivity to CO_2 doubling, etc., appear at least 2.6 standard deviations away from its current "best guess" value. For a random variable that is assumed to be normally distributed, the probability that the "true" value is more than 2.6 standard deviations from the current "best guess" is just 1%.

For the purposes of reasoned policy making, it is important to give some consideration to how the issue of risk perception enters into this operational definition of *de minimis* risk. Clearly, how we *perceive* and *respond* to societal risk influences, to a large extent, what is ultimately deemed a "surprise."

There are studies which show that most people — often including those who are quantitatively literate — do not respond to risks in the purely quantitative manner that is implied by our attempts to make quantitative estimates of the risks and their uncertainties. For example, Kasperson (1992) has discussed a "social amplification of risk," whereby people amplify in their minds the magnitude of risk depending upon a number of factors. There probably is also a "social contraction of risk," but that is of less importance in public policy, because of a tendency to pay attention to the most sensitive or most concerned individual(s).

Differences in lay vs. expert perceptions of risk can often be illuminated by comparisons. For example, Dickinson (1986), as noted earlier, used a lognormal fit of various estimates of global warming to estimate that there is a 5% in a lifetime chance that an increase in greenhouse concentrations would, by the year 2100, lead to a temperature rise of 10°C. If this 5% chance were to obtain during that time period, such an event would almost surely come as a "surprise" to many people, the reason being that it would give rise to adverse consequences that were largely unanticipated by them. It is interesting to note, however, that public opinion polls suggest that many people are unconcerned about a 5% (calculated by an "expert") of a climate-related catastrophe within their lifetime. We are ardpressed to attribute this view to ignorance, because climate change has now entered the political consciousness with the election to the Vice-Presidency of the United States the author of a popular book on the subject (Gore 1993).

These observations notwithstanding, it is worth noting that the public *is* concerned about a 1% chance of a nuclear accident (also calculated by an expert) in the same time period. We also note that an airliner with a calculated chance of failure far lower than 5% in its 30 year life would not be allowed to fly in commercial service. Does that mean that the public trust the experts on climate change more than the experts on nuclear power? Most students of risk assessment would assign the difference to an *outrage factor* associated with involuntary, insidious, or unfair practices of the nuclear and airline industries. That could be either considered as a reason for less trust, or as an important qualitative difference that cannot be altered.

There are no simple answers for the particular reasons why people differ in their perceptions of, and reactions to, risk. Nevertheless, if the nature of the uncertainties that underlie problems such as global climate change is not clearly articulated and understood, then confusion may arise even among the best experts. For example, Clark (1989), referring to Dickinson's analysis, notes that the chance that the world of 2100 will have witnessed a single nuclear power catastrophe is anywhere from 10 to 100 times less than the chance that everyone in the world will be living in the Mesozoic greenhouse. He concludes that "this assessment jars common sense, which is exactly why we need to reexamine the assessment methods and philosophies that produced it as an urgent task of understanding global environmental change."

For chemical carcinogens, it is common to discuss a risk to an individual of 10^{-6} in a lifetime of 70 years. This is a far smaller number than the probabilities of a huge temperature rise and catastrophic effect in the next 70 years. Following Clark (1989), we ask whether it means that EPA is too conservative in taking this small number for chemical carcinogens, too optimistic about global warming, or whether the comparison is alltogether invalid? As discussed earlier, in order to avoid the confusion shown in the citation above, we have to make a clear distinction between stochastic uncertainties and uncertainties of fact.

6. OVERCONFIDENCE IN EXPERT JUDGEMENT: IMPLICATIONS FOR CLIMATE CHANGE POLICY

A clear message from the history of science is that unexpected uncertainties in models and parameters are quite common, and that new results are often far away from old values. In interpreting the predictions of climate change models, scientists recognize this, and often recommend cautious action accordingly. Recent work shows how this can be more formally addressed. The long record of measurements of physical constants (such as the masses of elementary particles) prompted several early studies of the temporal evolution of uncertainty (Hampel *et al.* 1986, Henrion and Fischoff 1986, Shlyakhter *et al.* 1992, 1993a,b, 1994a,b,c) expanded upon these original studies by examining trends in several data sets derived from nuclear physics, environmental measurements, and energy and population projections.

Over decades, measurements improve sufficiently that we may consider the present measurements as the "truth," and earlier measurements as mere approximations thereto. With hindsight, we can ask whether the old measurements obtained the correct result to within the stated error. Similarly, in the case of global climate change, stated uncertainties in the old projections of important parameters, such as population growth and energy consumption, can be compared with the actual errors after the target dates have passed.

More precisely, we can derive a ratio, x, of the subsequently determined error in the old measurement to the author's stated estimate of error $x = (a - A) / \Delta$, with a, the new value, A, the measured value, and, Δ, the old standard deviation. For projections, we use the range between the reference (central) projected value and the lower (or upper) projected value as a substitute ofor the standard deviation of the equivalent normal distribution. This corresponds to assigning 68 percent confidence to the reported uncertainty range. If the errors were random, one would expect the distribution of x to be normal (Gaussian), with standard deviation of unity. However, as Figures 5 and 6 illustrate, there are deviations from the Gaussian distribution in the tails. In order to make these deviations stand out, we have plotted the figures using a logarithmic scale. Inspection of the figures showsThis shows that the data deviate from the Gaussian tail by a large factor, although the absolute deviation could be considered to be small. Note that we have left out of our analyses the cases of extremely large errors ($|x|>10$) arising from blunders or the use of wrong models.

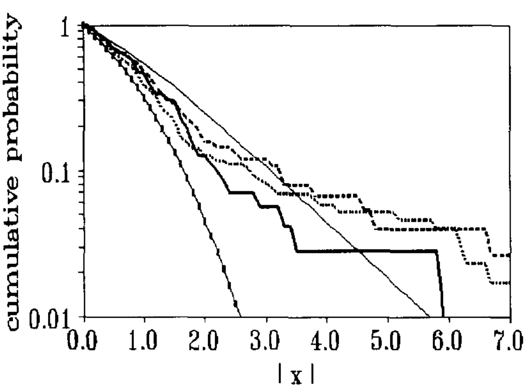

Figure 5. Probability of unexpected results in physical measurements. The plots show the cumulative probability that new measurements will be at least | x | standard deviations away from the old results for particle data (heavy solid line), for magnetic moments of excited nuclear states (dotted line), and for neutron scattering lengths (heavy dashed line). Also plotted is the cumulative normal distribution, erfc($x/\sqrt{2}$) (thin solid line with markers), and the compound distribution with parameter u=1 (solid line). Note the logarithmic scale, which is used here to emphasize the differences in the tails of the distributions.

The cumulative distribution of $|x|$ can be approximately described at large values of x (corresponding to large errors) by a compound distribution with both the mean value and the standard deviation following a normal distribution. At large values of x, this compound distribution is described by the exponential function exp($-|x|$ / u), where u is a new parameter that describes the frequency of unrecognized errors; larger values of u correspond to more common underestimation of uncertainties. Using statistical analysis of past errors, one can develop safety factors for current models (Shlyakhter 1994b,c). Fits to physical measurements give u = 1; fits to the national population projections (Shlyakhter and Kammen 1992, 1993a) give u=3; fits to a set of U.S. energy projections give u = 3.4 (Shlyakhter *et al.* 1994a).

The results for population projections are shown below in Figure 6. The population data base includes projections from 164 nations, and consists of an average of the "high" and "low" variants of the United Nations Population Studies series (UN 1991). The projections were made in 1972 for the year 1985. Data for 31 countries was excluded because of extreme errors. Data for 133 nations satisfying the criteria | x | < 10 are included in the analysis. Because all of the estimates come from an authoritative source, namely, the United Nations, it might be expected that systematic errors would be small, representing a well-calibrated model. However, the unrecognized uncertainty is very large.

The central issue we wish to stress in this paper is the application of this concept to predictions of global warming and its effects. Are the predictions as reliable as measurements of physical constants, more reliable (u=0), or less reliable (u=3)? Only after this question is addressed can we properly address Dickinson's question of how to consider an extreme temperature rise.

One can view the collection of all ΔT_s predictions from a set of available General Circulation Models as a random sample derived from a larger set of predictions of all possible models. We do not know whether the current models cover all possible values of ΔT_s. We assume that with probability α, the *true* value is within the range of reported values. Let us assume that α=99 percent; the standard deviation of the equivalent normal distribution is then 2.575 times less than half the width of the interval between the lowest and the highest model results. Note that in estimating u values for measurements and projections, we use α=68 percent for the reported uncertainty range. Therefore, we assume that the collection of current climate models almost certainly covers the true value of ΔT_s. Had we assumed that level of confidence for the old forecasts, the derived standard deviations would be smaller, and all x values would be larger. The resulting u values and the corresponding inflation factors would also be larger than the ones actually used.

Since ΔT_s is determined by the value of the sum of all feedbacks, f, we convert the range of ΔT_s values into the range of f values. For example, ΔT_s=1.9°C gives f=0.37 and ΔT_s=5.2°C gives f=0.77. This range of f values can be used to estimate the standard deviation of the equivalent normal distribution in the same way as for the energy and population projections discussed earlier.

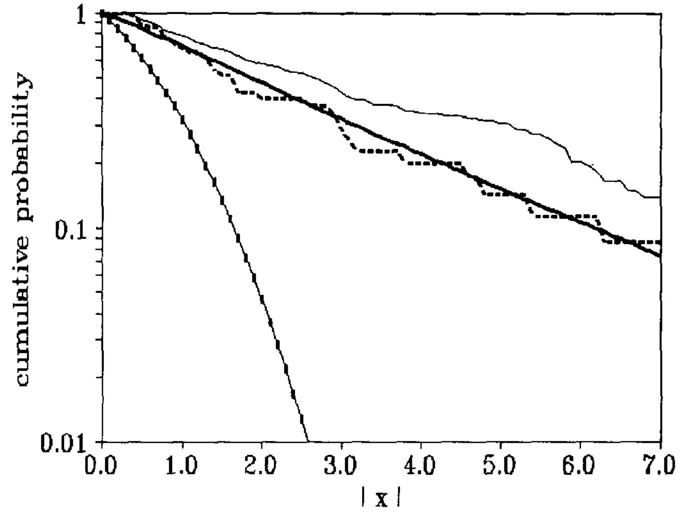

Figure 6. Population projections (Shlyakhter and Kammen 1992, 1993a). The plots depict the cumulative probability that "true" values will be at least | x | standard deviations away from the reference value of old projections. The cumulative probability distributions of |x| are shown for the total data set of 133 countries (solid line), and for a subset of 37 industrialized countries (heavy dashed line). Also shown are the normal distribution (solid line with markers) and the compound distribution with u=3 (heavy solid line). Note the logarithmic scale, which is used here to emphasize the differences in the tails of the distributions.

The corresponding distribution of ΔT_s values is shown in Figure 7, together with the exponential distribution for u=1 and the distribution of ΔT_s from 21 General Circulation Models (Cubasch and Cess 1990). By using the exponential distribution with u=1, we assume that the fraction of unrecognized errors in climate models is similar to the fraction of unrecognized errors in physical measurements.

With the normal distribution, there is 1% chance that the true value of ΔT_s exceeds 5°C, while with the exponential distribution, the same probability corresponds to a catastrophic increase of more than 10°C. In a simple feedback description, $f \approx 1$ would result in a catastrophic runaway warming. Although the true picture will be much more complex, and negative feedbacks will probably limit the warming, the possibility of CO_2 atmospheric buildup that could lead to a runaway warming and to a switch to a different climate equilibrium must be avoided at all costs. This possibility leads us to suggest that *prudent* policy decisions should be based on the exponential as the "default" distribution, rather than on the normal distribution. Policy decisions based on more *optimistic* views of future temperature rise would require further justification. Many societal decisions seem to be governed by a belief that we should be very careful to avoid situations with global consequences, even if there is a small probability for their occurrence. This view must therefore be tempered with any information that might seta firm limit on possible outcomes. A study of the historical record might provide such information.

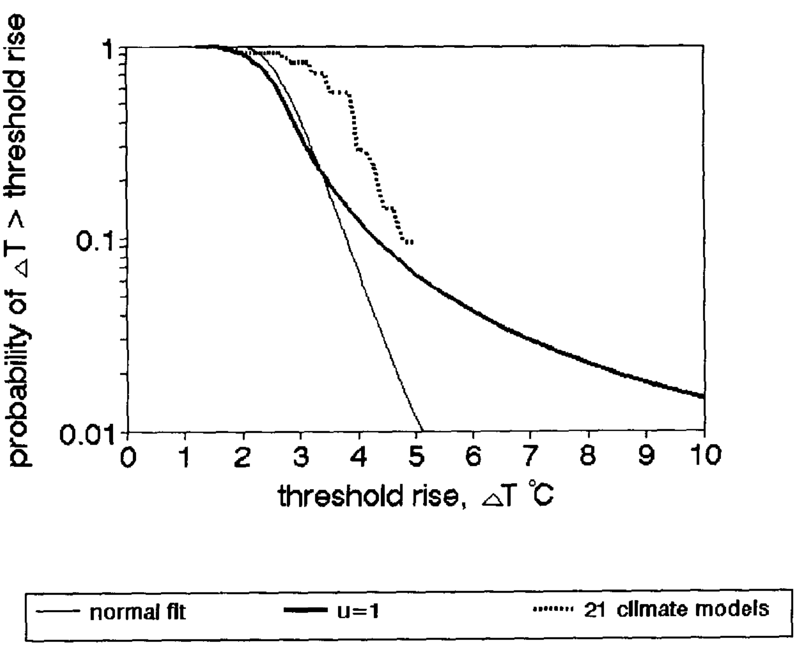

Figure 7. Estimates of the mean-surface global temperature rise in response to doubling CO_2 concentration. The cumulative probability of a temperature rise, ΔT_s, greater than a given threshold is plotted for the normal distribution of uncertainty in the feedback factor f (solid line), the exponential distribution with $u=1$ (as described in section 5), and the distribution of the ΔT_s values from 21 global circulation models (Houghton *et al.*, 1990).

The distribution may be truncated by bringing in other information not considered by the GCMs. In particular, we can examine historical global climate trends to determine whether they are consistent with the extremes of such a distribution. This procedure is used in Figure 8 to compare the observed global-mean temperature changes during the last century with predicted values (Wigley and Barnett 1990). The global temperature rise attributable to CO_2 doubling can be estimated from a visual inspection of such curves. Figure 8 clearly illustrates that the main rise occurred before 1940 (as noted in the introduction), and we see the rise in temperature since 1980, which brought the subject to public attention, although it is smaller than the model predictions.

The models before 1992 did not include the effects of fine particulates — including sulfates — that have spread over the northern hemisphere from fossil fuel burning. These particulates have a cooling effect (Hansen and Lacis 1990), as does the ozone depletion in the upper atmosphere that has been observed in recent years. That there might be a cooling of aerosols has been known for a long time but has only recently been included. It is probably masking the effect of the rise in the CO_2 concentrations (Charleson *et al.* 1992, Taylor and Penner 1994). There is pressure to reduce aerosols

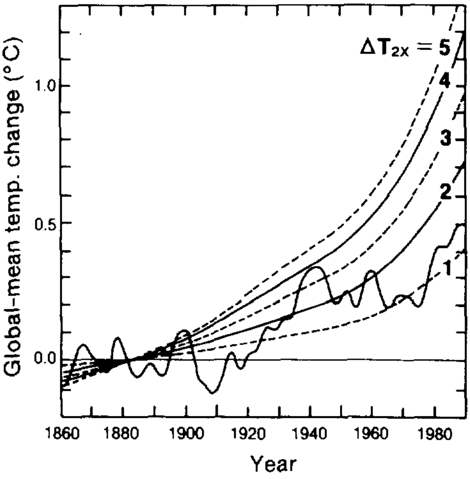

Figure 8. Observed global-mean temperature changes (smoothed to show the decadal and longer time scales trends more clearly) compared with predicted values for several values of ΔT_s (shown on the curves) (Wigley and Barnett 1990).

from those who believe that they contribute to adverse effects on public health. To the extent that these efforts are successful, global warming may become worse, and therefore be identifiable.

Michaels *et al.* (1994a) have carefull compared the predictions of the models with recent temperature records. They note that if the sulfate explanation is correct, then the models should work best in regions where sulfate concentrations are lowest, namely, in the southern hemisphere and high latitudes. This expectation does not seem to hold, however. Michaels *et al.* (1994b) also find no correspondence between observed and predicted temperature trends during the times of longest day (in the summer) and longest night (in the winter) when the models predict the largest effects. This result shows that the models *in their present form* do not seem to describe what is occurring in as much detail as we would like. The observations, however, do seem consistent with the idea of a negative feedback effect cancelling the warming trend.

It is crucial to emphasize, however, the fact that a comparison of the historical record to the models does not unequivocally show an effect of increased greenhouse gases *does not* prove the inverse, i.e., that no effect is occurring. This point was emphasized by Duffy (1993). It seems that there are at least three effects of approximately equal magnitude: CO_2 forced warming (described by the models), aerosol forced cooling (only recently described by the models), and natural variability with causes of source unknown. In evaluating public policy options, we are therefore left with the general arguments refered to in the introduction, namey, that society is making large changes in an important climate parameter — CO_2 concentrations — on a short global time scale. Given this state of affairs, should society wait until an adverse effect has been definitively proved, or, alternatively, should society try to reduce the changes in CO_2 concentrations until our models show definitively that nothing adverse is occurring? Nevertheless, it does seem that a temperature rise, ΔT_s for static CO_2 doubling larger than 6°C, although possible, is unlikely (Wigley and Barnett 1990, Wigley and Roper 1991). Kondratyev and Galindo (1994) emphasize that the argument that global warming may be more remote than IPCC assumes is best addressed by a more careful look at climate change and "ecodynamics," and they summarized the recent progress to this end.

In the preceding discussion, we have expanded the uncertainty distribution to take account of unrecognized uncertainties, and have suggested a way of contracting it again by consideration of historical trends. Another way of constraining possibilities, in this case constraining the fourth factor in Equation (1), has been suggested by Lindzen (1994). Noting that simple box-diffusion-upwelling models give us useful insights into the dynamics of ocean heat transfer, he suggests that the time scale τ corresponding to the time it takes for ΔT to reach (1-1/e) of its equilibrium value after it has been forced, and ΔT_{2xCO2} might be constrained by a study of the response to volcanos. Analysis of the mean global temperature record following a number of major eruptions in 1883—1912 suggest that the cooling effects of successive volcanos did not add up. This implies that τ might be less than 16 years and ΔT_{2xCO2} might be less than 0.6°C — far lower than the limits so far suggested for tese parameters. Clearly, there are concerns about the application of a study of short term incidents to long term continuous changes, but even if Lindzen (1994) is overly optimistic by a considerable factor, any upper limit would be important if it can be defended in such a way as to achieve consensus among most scientists.

The distributional uncertainty in each of the factors in Equation (1) has been shown to have longer tails than the normal distribution. Does that mean that the simple formula for combining lognormal distributions is inapplicable? This is a problematic issue, which we only mention here. Since the initial uncertainty estimates in measurements and forecasts were, in fact, the estimates of combined uncertainties from several factors, we believe that it would be inappropriate to combine the individual exponential distributions. Instead, we propose to combine uncertainties in the individual factors in Equation (1). After the combined uncertainty for the impact of interest is evaluated, one can then hedge against the unaccounted errors. First, we begin by assuming an exponential distribution instead of a normal distribution or errors, derive an appropriate safety factor. This can be done by comparing the x values observed in historical data sets (at a specified frequency) to the x values for which the same probability is predicted by the normal distribution.

The procedure outlined above can easily be adapted to discussions of sea-level rise by replacing the normal distribution of uncertainties used by Oerlemans (1989) with the exponential distribution. This procedure is illustrated below in Figure 9, which suggests that there is a 1 percent chance of 2.5 meters sea level rise by the year 2100. Most observers would say that this is impossible. This judgement, like the similar judgments about temperature rise, are based not on model parameters, but rather on historical experience. Simply drawing probability distributions neglects historical experience. The constraints imposed by historical experience are not simple, and must themselves be imposed by applying the model. Imposing these constraints is not simple, because the model predictions that are compared are for the artificial equilibrium world of constant CO_2 concentrations, and there are time delays in translating concentrations to temperature rises. However, in applying this historical constraint, we may be able to show that the probability of the extreme event is less than typically calculated.

The need to truncate the probability distributions also appears in the models that calculate the risk of cancer from chemical carcinogens. The uncertainty, particularly in the animal / human comparison, is great, so that if one is interested in the upper 95th percentile of a distribution, an unreasonably large number of cancers is sometimes predicted. This problem was emphasized by Ennever *et al.* (1987), and discussed further by Goodman and Wilson (1991). The probability distribution for the number of cancers must be truncated at a value corresponding to the maximum number that could exist without them having been measured.

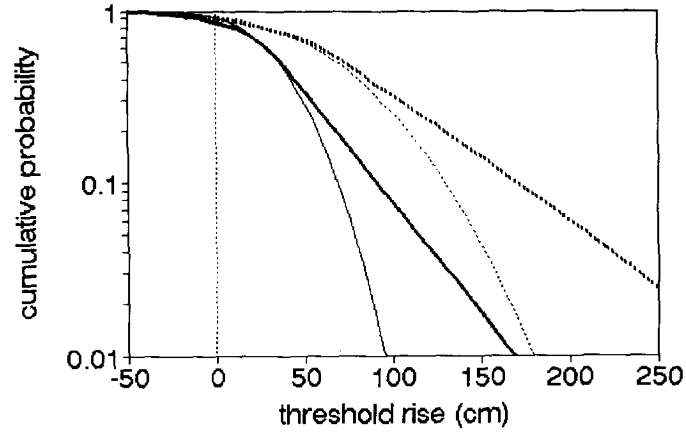

Figure 9. Projections of sea-level rise for 2050 A.D. and 2100 A.D. The probability of a sea-level rise greater than a given threshold is plotted for the normal distribution of errors (2050: thin solid line; 2100: thin dashed line) and for the compound distribution with u=1 (2050: heavy solid line; 2100: heavy dashed line). Note that a fall in sea-level is also possible. Note, also, the logarithmic scale, which is used here to emphasize the tails of the distributions.

We have discussed the issues presented in this section with many scientists more expert on climate change than ourselves. As the analysis above suggests, the distribution of opinion about the predicted temperature rise is wider than that suggested by IPCC or NAS; some say that $\Delta T/CO_{2atmos}$ (Factor 5) is close to zero; another who disbelieves the models, because of their inability to describe the historical record, nonetheless puts it at the lower bound of the distributions; still others might put it at three times the IPCC value. This observed variability is formally being addressed by Morgan and Keith (1993).

7. SEQUENTIAL DECISION-MAKING STRATEGIES

As discussed previously, the simplified model of Section 2 is a static model. The risk is estimated, with its uncertainty, at one period of time, and the decision on what, if anything, to do is made essentially simultaneously with the assessment. Of course, real life is not that simple. In an important subject such as global climate change, decisions on measures to avert or mitigate the effects of climate change will be made frequently over time. The assessment must then be an *iterative* process.

Any reasonable analysis of the potential risks of global climate change must address the general concern shared by many scientists that once the effects of global warming appear above some agreed upon "noise" level, the CO_2 atmospheric concentration will be so far advanced that the effects of warming will take centuries to reverse, if at all possible. It is here that the time constant for coupling to the deep oceans is critical. If this time constant is large, then it seems reasonable to suppose that action to prevent increased CO_2 concentration should be taken *before* the effect of this increase is conclusively verified.

The crucial question that must be continuously addressed therefore becomes "What actions, if any, should be taken about global warming when the effects have not yet demonstrated themselves unequivocally?"

The first decisions might be to take those actions where the cost is not high. In this regard, a much publicized article addressed the minimal agreement of three distinguished scientists with widely different views (Singer, Revelle, and Starr 1991). Together, they proposed three actions:

1. Conserve energy by discouraging wasteful use globally;
2. Improve efficiency in energy use;

3. Use non-fossil fuel energy sources wherever this makes economic sense.

Later, Revelle (1992) suggested three more possible courses of action:

4. Sequestration of organic carbon in deep sea by stimulating spring phytoplankton production in high-latitude oceans;
5. Sequestration of carbon in trees;
6. Increasing the Earth's albedo.

This minimal set of actions seems quite reasonable, yet none of these actions are currently being undertaken in the Unied States. It seems that, in spite of much political rhetoric, the U.S. and other countries are taking very little action.

As noted earlier, actions (1) and (2) are most easily achieved by an increase in the cost of the relevant fuels; yet, in 1993 an increase was rejected by the U.S. congress. In the past, Revelle, Singer, and Starr have advocated expansion of nuclear power. Needless to say, the present U.S. administration, while emphasizing global warming, is not following this particular course of action. Naturally, one cannot reasonably expect that the administration will accept all of the recommendations that scientists put before them. In particular, any emphasis on nuclear power might well be considered by some members of the public an overreaction to an uncertain threat, and introducing what, in their view, is a worse threat. Many people prefer to wait until society can try a combination of biomass, wind, and photovoltaic electricity. In the framework of risk analysis, this preference can be construed as a willingness to accept a delay in reducing global warming and a willingness to accept the uncertainty of whether the hoped-for result (economically attractive non-fossil and non-nuclear energy) can be achieved.

Several credible climate change experts have contemplated the actions that mankind might make in response to the threat of global warming (see, e.g., Stone 1994). There is no plan to stabilize the world wide CO_2 emissions at the 1990 level. Yet, even if this is done, it is likely that concentrations will rise to $3xCO_2$ within a century — well over the $2xCO_2$ analysts usually discuss. Thus, at the moment, there seems to be no clearly acceptable alternative available to policymakers.

Consensus on a more draconian set of actions might be achieved if the uncertainties in the assessment of outcomes were reduced and, moreover, if it could be demonstrated that CO_2 - forced global warming is actually occurring. However, a decade-long time scale is anticipated for narrowing the uncertainties in predictions of the rate of climatic change through improved coupled atmosphere-ocean models (McBean and McCarthy 1990).

A number of decision-making stategies for confronting the problem of global climate change have been put forth in recent years. Manne and Richels (1991), for example, develop an "act then learn" strategy for decision-making in the energy sector. They propose that decisions be made at discrete points in time (every decade). The value of new information depends on changes in the probabilities assigned to each scenario before and after the study. If the probabilities of three scenarios remain equal, then the value of the study is zero; if, on the other hand, only one scenario can be selected, a study might be worth as much as 100 billion dollars. Critics of such a strategy emphasize that it is sensible *only* if something is done in the time between the discrete assessments. Thus, the question always raised by decision analysts is, "What will you do (or expect to find out) in the available time?" If the answer is nothing, then there is no merit in postponing a decision.

In this paper, we have discussed several possible uses of the time. We summarize them here, but do not intend this as an exclusive list.

- Using the time to achieve political consensus. We believe that widespread understanding of the issues discussed in this paper will help in this regard.

- If some action is desired, policymakers might initially implement some or all of the minimal steps 1–6 listed above.

- Perform research in the energy sector to determine
  - The viability (economic and technical) of solar alternatives to fossil fuels;
  - Whether public acceptability of the nuclear alternative to fossil fuels will be

  achieved in the future (and what is necessary to achieve it).

- Perform studies on how to reduce "perverse" obstacles (such as institutional overhead) to energy efficiency.

- In an attempt to tie down limits on the possible effects of increasing GHG concentrations, perform research aimed at improving understanding of the physical and chemical processes determining climate change.

- Perform research to determine the manner and degree to which society can adapt to whatever climate change might actually occur.

These possible research programs are intended to provide information for making better decisions in the future. In general, there are two ways to approach the problem of valuing information (Hammit 1994). First, new information can refine the fundamentally correct, but imprecise, information characterized by a prior distribution. This is the phenomenon described in Section 6. Second, the new information can reveal that a prior distribution reflects overconfidence or fundamental misunderstanding. The conventionally defined value of information measures the first type of information value, but, because it is fundamentally dependent on the prior distribution, it cannot capture the second type. Stated another way, if the gain in information is measured by the expected decrease in the variance of a parameter, then an overly narrow prior distribution produces an underestimate of the gain, since the gain cannot be larger than the prior variance. For this reason, the probability of surprise should be explicitly taken into account when discussing the value of future research. As discussed in Section 6, the probability of surprise can be quantified by a statistical analysis of the frequency and magnitude of past errors.

8. BALANCING RISKS, COSTS, AND BENEFITS: OPTIMUM REDUCTION LEVELS

Another issue that arises in decisions about climate change is whether there is an *optimum* level of reduction of CO_2 emissions. In order to address this question, one must carry the risk assessment to its conclusion by assigning a financial cost to each and every impact, and then adding them together. As in all such situations, the marginal financial gain on reducing CO_2 emissions decreases with additional expenditures on the control of CO_2. According to several studies, the first 20 percent of emissions are averted cheaply (requiring less than \$1/ton CO_2 equivalent); the next 20 percent reduction will require up to \$10/ton; the next 20 percent require up to \$100/ton. If we are willing to pay \$1,000/ton, then another 20 percent can be averted (NAS 1991, Nordhaus 1991). There is, however, no feasible way to eliminate emissions completely, because the costs rise very steeply. Note that these numbers are not accepted by ardent proponents of a nuclear electric economy; proponents in this camp argue that 50% of energy use can be converted to nuclear electricity for a 20% cost increase, provided that societal fears do not increase the cost of nuclear electricity. This ardently pro-nuclear argument, although technically plausible, completely ignores the political, cultural, and economical realities presently faced by nuclear power throughout the world, nor are the numbers cited above accepted by proponents of a solar and energy efficient economy. Of course, further information may show that one or another (or even both) these possibilities are correct, and that the optimal level to which CO_2 can be reduced is very low. Policy analysts and decision makers who believe that this view might be correct should therefore assign considerable value to obtaining the relevant information.

There are, as yet, no similar large-scale analyses of expected losses versus efficiency of controls. One might expect that for low efficiency of reductions, much higher losses can be attributed to each additional ton of greenhouse gases than for a highly efficient reduction action, when global warming is small anyway. This view is supported by a study by Yohe (1991) of economic vulnerability vs. the sea level rise for Long Beach Island, New Jersey, U.S.A. The sum of losses and mitigation costs, i.e.,the total expenditure, has a minimum, indicating the optimal efficiency of emissions reduction. This minimum is schematically illustrated in Figure 10.

The optimality depicted in Figure 10 holds only for a particular path down the scenario tree presented in Figure 2, in that the expected losses for different scenarios vary. Of course, we have oversimplified the problem in many respects. For example, discount rates relating expenditures today with future benefits must be explicitly incorporated. If the probability values were known for each scenario, one could estimate the appropriate mitigation costs for a particular outcome, and then come up with a probability distribution of the optimal efficiencies. Eventually, such a distribution could be used to translate the uncertainty in predictions of global warming into the uncertainty of the goals that policy makers must formulate.

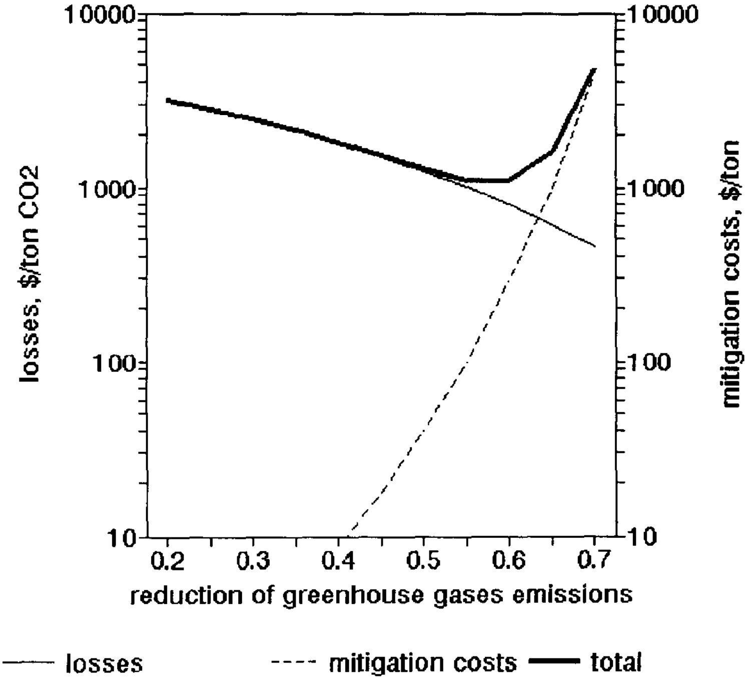

Figure 10. Damages from not reducing emissions (losses) and mitigation costs *vs.* the fraction of emissions averted (schematic layout).

Dowlatabadi and Morgan (1993) used their ICAM-1 model to study uncertainty in climate sensitivity to changes in radiative forcing. In this study, they first ran the model with the present uncertain value for climate sensitivity, and then obtained estimates of the expected net present value of each of several policy options. The model then assumed that a research program designed to improve our understanding of climate sensitivity is launched, and then considered a set of possible values that the mean and variances of their estimates might assume after the research is complete. If research reveals that the expected cost of the preferred policy has declined from an expected value of *D* to *D* - *d* as a result of the new knowledge, then society has d more disposable income to support consumption or investment than it originally had expected to have. If research reveals that the expected cost of the optimum policy goes up from D to $D + d$, then society must reallocate its other expenditures and investments to secure the additional resources d. The problem is to assign a monetary value of learning ahead of time, whether the current policy is an optimal one, and whether it will cost more or less than originally thought. This approach combines steps 5 and 6 of the causal progression presented in Section 2. While promising, at the moment, this procedure has too much uncertainty to be useful for public decision-making.

9. INTERREGIONAL AND INTERGENERATIONAL EQUITY

One of the most obvious public policy concerns about global climate change is that of interregional equity. Each person who emits, or allows someone else to emit, one of the greenhouse gases gains (or perceives that he gains) some benefit. However, the increase in global warming happens all over the world, and the risk initially caused by the gaseous emission may be incurred by completely different people. Clearly, intergenerational equity is important also, in that future global warming depends, in part, on past CO_2 emissions.

CO_2 has, in the past, been emitted primarily in industrialized countries. Already, any global warming that may have occurred is a problem for other countries as well. Any risk of adverse impact may fall on particular groups whose boundaries are not defined by their industrial development.

Society has developed a variety of tools for coping with interregional inequities. The most obvious is a transfer of payment, by taxation or otherwise, from those gaining the benefit to those incurring the risk. It is easier, and perhaps fairer, to make a risk-related decision when the risks are borne by the same person or group to whom the benefits accrue. If the risk of an action exceeds the benefit perceived by that person, then the action will not proceed. However, if the person who bears the risk is different from the person to whom the benefit accrues, and if the risk bearer is willing to value risk lower than the benefactor values the benefit, then it may be possible to achieve a net excess of benefit over risk for each party; this might be achieved by some charge of payment, whereby the party who benefits compensates the party who bears the risk. Although by such a monetary transfer the risk/benefit decision for each party becomes favorable, there is the complication of deciding upon the exact payment; one party may benefit (overall) more than the other, and negotiation(s) may be time-consuming. In fact, the time and effort needed to make the negotiated transfers themselves become an additional cost.

Even when there are several groups, this procedure might be generalized to ensure that the risk/benefit balance is positive for each affected group of importance. A similar concept applied to technological risk has been advanced by Fischhoff (1994). Clearly, the manner and degree to which *existing* institutions are able to effectively apply this conception of acceptable risk is a matter of considerable debate. Nevertheless, it is useful to consider how simple conceptions of interregional equity can be applied to the problem of global climate change.

The Earth Summit at Rio de Janeiro in June 1992 illustrated the importance of interregional equity. In particular, third world countries with little industrial development argued that it was not for them to reduce emissions of greenhouse gases, or, for that matter, to encourage their absorption by retention of rain forests, unless appreciable transfer payments came from those countries who are producing the major emissions.

This important fact suggests a possible change of policy. Instead of spending money in the United States to reduce emissions of greenhouse gases, why not consider paying another government to reduce them? While initial applications of this idea are for financial contributions of the United States government to an overseas government, this might be extended to payments for specific tasks, such as helping otherwise unprofitable hydroelectric, nuclear, or solar power plants. Such fiscal measures as tax incentives, based upon the number of CO_2 molecules reduced might bring the private sector into a productive role. Interesting studies are currently underway on whether paying the Chinese to consider non-fossil fuels for their energy expansion will be a cost effective way for the U.S. to spend its CO_2 reduction dollars.

This line of reasoning suggests that economic adjustments can be considered for intergenerational equity, as well as for interregional equity. A person (or society) can, and perhaps should, make appropriate investments to pay for the cost of possible future consequences. Raiffa *et al.* (1977), in a classic paper, argue that future "lives" in the risk/benefit equation should be discounted at the same rate as money. Their argument is that money can be invested now, at the monetary discount rate, and at the time the hazard arrives, the money has been appropriately increased by the interest accumulated. If it is proper to discuss a relationship between the amount one is willing to pay to reduce a hazard and the benefits one gets from the reduction, then it is also appropriate to discount that amount with the usual monetary discount rate.

The money could be set aside for "balancing" the risk over future generations, as well as for finding a way to avoid the risk. Money might be invested in avoiding some other comparable risk, such as cancer, which in the future would otherwise add to the risk of global warming.

Many economists would agree with Raiffa *et al.* (1977) that society would be more efficient if people, especially managers, adopted this approach to future risks. However, many examples show that people do not. Here, we discuss two such examples, and we suggest that if a discounting formula is to be used, then the discount rate should be left as a free variable until there is more understanding of how society wishes to operate.

With a 5% discount rate, the investment that is necessary to reach a capital sum of $1,000,000 after a couple of generations — about 60 years — is small. Most people will not worry about most decisions over a period longer than that; we think about our grandparents and our grandchildren, but do not often think much further. Of course, there are exceptions, and these exceptions almost invariably seem to involve major societal decisions.

Some people expect that society as a whole should approach such decisions in a logical and consistent way. Some simple examples suggest that this is not the case. A simple risk/cost/benefit decision about nuclear waste might proceed along the following lines. If, for example, we take an amount to save a life of $1,000,000 (corresponding to the $1,000 per man-rem suggested by the Nuclear Regulatory Commission in 1975 in their discussion of the ALARA principle in RM-30-2), and we take a discount rate of 5 percent, then we should be prepared to put down $\$1{,}000{,}000/(1 + 0.05)^n$ per life, where n is the number of years over which we discount. For a hazard in 100 years time, we should invest $7604. For a hazard in 1,000 years, this becomes $58. For a maximum of 1000 cancers caused by a possible leak of a high level nuclear waste repository in a 1000 years time, this would be an "up front" charge of $58,000. Such an amount is far from the billions of dollars now being spent for this purpose. Clearly, our societal decision making is not working this way, whether from intent or from accident. If the difference is unintentional, it should be easy to correct. Naturally, these issues remain a matter of considerable debate, and we raise them as questions that policy analysts, risk managers, and decision makers must eventually confront.

The application of this line of reasoning to toxic chemical waste is somewhat different. The differences come primarily in the regulation and the demand for what are called "secure landfills," which are intended not to leak for 50 years. The depth of this time horizon is in sharp contrast to the nuclear case, where water reportedly should not leak at all for 500 years and, moreover, can have only a small leak rate beyond that. There are cases where a supposedly secure landfill has leaked before 50 years. In addition, the usual definition of a secure landfill seems to be based on the unproven presumption that toxic chemical waste will not be toxic after 50 years. This might be true if the waste were exposed to environmental factors, such as ultraviolet light and other natural means of breaking down complex chemicals. The presumption seems far less likely to be true, however, for a landfill where the waste is essentially isolated from the environment.

One possible reason for the differences in the two instances may be that, for nuclear waste, the failure of a high level waste repository is perceived as an irreversible disaster, whereas the failure of a toxic chemical waste site is merely regarded as a large hazard. Of course, the geographical extent of the impact and the time needed for ecological recovery are also relevant considerations.

Given the differences in these two cases, it is difficult to find a simple analogy to global climate change. Is the situation for intergenerational equity like that for nuclear waste, where attention must focus on what happens 5,000 years from now, or is the situation more like the case of chemical waste, where the implicit hope is that 50 years will tell us whether there is a hazard, as well as give us some idea of what we can do better or what we can improve upon? As we have already said, climate change can potentially have long-enduring impacts if, for example, ecosystems are totally disrupted, and if observed impacts are felt globally. However, many impacts (such as floods and droughts) may appear indistinguishable from local hazards, and they might cause stress only for a period of decades as adaption occurs.

Naturally, societal views on such matters can change over time. Fifteen years ago, society was not concerned about global warming. When some scientists said that the global warming might, within a century, be significant enough to melt the polar ice cap and flood New York City, they were met with alternate skepticism (which has turned out to be appropriate, since now the predicted sea-level rise is much less than originally thought) and resignation.

10. CONCLUSION

By contemplating the process of integrated risk analysis of global climate change, we have shown how the calculation of risk proceeds by considering a number of nearly independent steps. Serious problems remain, however. Most of the GCMs that have been designed to describe the effect of increasing CO_2 concentrations fail to describe important regional details; few seem to get the changes correct over a 10 year time span, and all may be completely wrong over time scales spanning many thousand years.

An important feature of risk management related to climate change seems to be the feeling among both scientists and the lay public that we should take an insurance policy, which simply amounts to considering the *upper limit* of a probability distribution of impacts (Schelling 1991). This upper limit is, in many respects, ill-defined, but can be quantified using a *de minimis* concept of risk. In this context, however, it must be defined for non-stochastic uncertainty. This conception of risk distinguishes between scenarios that are believed possible and those that are rejected as improbable. Empirical evidence suggests that overconfidence in predictions of future development results in long tails of the distribution, and therefore in unexpectedly high probabilities of surprise. These tails can, in principle, be truncated by using additional information, such as model-independent restrictions on climate change from paleoclimatic data, or from volcanic eruptions. To this end, efforts must now focus on learning how to translate the large body of contradictory information about past and present climate into defensible upper limits on the probability of surprise. We believe that integrated risk analysis of global warming and its impacts should become a working tool for decision makers and risk managers in illuminating the important scientific issues and uncertainties that frame the global climate change debate.

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