Schneider, S.H., A. Rosencranz, and J.O. Niles, (eds.), Climate Change Policy: A Survey, Island Press, Washington D.C., 2002.

CHAPTER 2

Uncertainty and Climate Change Policy

Stephen H. Schneider and
Kristin Kuntz-Duriseti

Given modern satellite technology, it is ironic that the thinning of the ozone layer over the South Pole in the late 1970s went undetected for years. The satellite instrumentation did not fail; rather, the computer programs written to analyze the vast volumes of satellite data were instructed to reject measurements that diverged sharply from expected normal conditions. Amazingly, the rejected values were called to no one's attention. Noticing outliers in ground-based records of ultraviolet (UV) radiation reaching the earth's surface at a British station on the coast of Antarctica,[1] incredulous British scientists plotted the data by hand. To the surprise of all, they discovered a steady decrease in the ozone in the Southern Hemisphere springtime from the mid-1970s to the mid-1980s. This unexpected phenomenon immediately triggered a reprogramming of the U.S. computers to analyze all data points and revealed a deep hole in the ozone over the Antarctic continent, which was growing in intensity over time and drifting over nearby oceans and continents. This example shows that sometimes the knowable remains undetected because of the assumptions that frame the question or methods of analysis.

It is almost a tautology to note that unexpected global changes such as the development of the hole in the ozone layer are inherently difficult to predict. It is equally noninformative to suggest that other climate "surprises" can arise in the future. Yet despite the difficulty in forecasting climate change and its consequences, it remains imperative to address the wide uncertainties in our understanding of climate change and its effects. Global change science and policymaking will continue to deal with uncertainty and surprise. Therefore, more systematic analysis of surprise issues and more formal and consistent methods of incorporating uncertainty into global change assessments will become increasingly necessary.

Significant uncertainties plague projections of climate change and its consequences. The extent of the human influence on the environment is unprecedented: Human-induced climate change is projected to occur at a very rapid rate; natural habitat is fragmented by agriculture, settlements, and other development activities; exotic species are imported across natural barriers; and we assault our environment with a host of chemical agents.[2] For these reasons it is essential to understand not only how much climate change is likely but also how to characterize and analyze the effects of climate change.

The combination of increasing population and increasing energy consumption per capita is expected to contribute to increasing CO_2 and sulfate emissions over the twenty-first century. However, projections of the extent and effect of the increase are very uncertain.[3] Central estimates of emissions suggest a doubling of current CO_2 concentrations by the mid–twenty-first century, leading to projected warming of more than 1°C to nearly 6°C by the end of the twenty-first century.[4] Warming at the upper end of this range is even more likely beyond a doubling of CO_2, which is likely to occur during the twenty-second century in most scenarios. Although warming at the low end of the uncertainty range could still have significant implications for species adaptation, warming of 5°C or more could have catastrophic effects on natural and human ecosystems, including serious coastal flooding, collapse of thermohaline circulation (THC) in the Atlantic Ocean (i.e., changes in the Gulf Stream currents), or nonlinear responses of ecosystems.[5] The market value cost of these impacts could easily run into many tens of billions of dollars annually[6] to perhaps as much as trillions of dollars by the late twenty-first century.[7]

Policymakers struggle with the need to make decisions that have far-reaching and often irreversible effects on both environment and society with sparse and imprecise information. Not surprisingly, efforts to incorporate uncertainty into decision making enter the negotiating parlance through catchphrases such as “the precautionary principle,” “adaptive environmental management,” “the preventive paradigm,” and “principles of stewardship.”[8] The shift toward prevention in environmental policy “implies an acceptance of the inherent limitations of the anticipatory knowledge on which decisions about environmental [problems] are based.”[9]

Uncertainty or, more generally, debate about the level of certainty needed to reach a firm conclusion is a perennial issue in science. The difficulties of explaining uncertainty have become increasingly salient as society seeks policy advice to deal with global environmental change. How can science be most useful to society when evidence is incomplete or ambiguous, the subjective judgments of experts about the likelihood of outcomes vary, and policymakers seek guidance and justification for courses of action that could cause significant environmental and societal changes? How can scientists improve their characterization of uncertainties so that areas of slight disagreement are not perceived as major scientific disputes, as occurs all too often in media or political debates? Finally, how can policymakers synthesize this information and formulate policy? In short, how can the full spectrum of the scientific content of public policy debates be assessed fairly and openly?

Decision Making Under Uncertainty

The term *uncertainty* implies anything from confidence just short of certainty to informed guesses or speculation. Lack of information obviously results in uncertainty, but often disagreement about what is known or even knowable is a source of uncertainty (Box 2.1). Some categories of uncertainty are quantifiable, yet other kinds cannot be expressed readily in terms of probabilities. Uncertainties arise from such factors as linguistic imprecision, statistical variation, measurement error, variability, approximation, subjective judgment, and disagreement. These problems are compounded by the global scale of climate change, but local scales of impacts, long time lags between forcing and response, low-frequency climate variability that exceeds the length of most instrumental records, and the impossibility of before-the-fact experimental controls. Moreover, because climate change and other complex sociotechnical policy issues are not just scientific topics but also matters of public debate, it is important to recognize that even good data and thoughtful analysis may be insufficient to resolve some uncertainties associated with the different standards of evidence and degrees of risk aversion or acceptance that people participating in this debate may hold.

In dealing with uncertainty in science or the policy arena policymakers typically consider two options: bound the uncertainty or reduce the effects of uncertainty. The first option is to reduce the uncertainty through data collection, research, modeling, simulation, and so forth. This effort is characteristic of normal scientific study. The objective is to overcome the uncertainty—to make known the unknown. However, the daunting uncertainty surrounding global environmental change and the need to make decisions before the uncertainty is resolved make the first option difficult to achieve. That leaves policymakers an alternative: to manage uncertainty rather than master it. Thus, the second option is to integrate uncertainty into policymaking.

The emphasis on managing uncertainty rather than mastering it can be traced to work on resilience in ecology, most notably by Holling.[11] Resilience is the ability to recover from a disturbance without compromising the overall health of the system.

BOX 2.1. Examples of Sources of Uncertainty[10]

Problems with Data

- Missing components or errors in the data
- "Noise" in the data associated with biased or incomplete observations
- Random sampling error and biases (nonrepresentativeness) in a sample

Problems with Models

- Known processes but unknown functional relationships or errors in the structure of the model
- Known structure but unknown or erroneous values of some important parameters
- Known historical data and model structure but reasons to believe that the parameters or model structure will change over time
- Uncertainty about the predictability (e.g., chaotic or stochastic behavior) of the system or effect
- Uncertainties introduced by approximation techniques used to solve a set of equations that characterize the model

Other Sources of Uncertainty

- Ambiguously defined concepts and terminology
- Inappropriate spatial or temporal units
- Inappropriateness or lack of confidence in underlying assumptions
- Uncertainty caused by projections of human behavior (e.g., future consumption patterns or technological change), which is distinct from uncertainty from "natural" sources (e.g., climate sensitivity, chaos)

The fields of mathematics, statistics, and physics independently and concurrently developed methods to deal with uncertainty. These methods offer many powerful ways to conceptualize, quantify, and manage uncertainty, including frequentist probability distributions, subjective probability and belief statements of Bayesian statistics, and even a method for quantifying ignorance.[12] Addressing other aspects of uncertainty, fuzzy set logic offers an alternative to classic set theory for situations in which the definitions of set membership are vague, ambiguous, or nonexclusive.[13] More recently, researchers have proposed chaos theory and complexification theory to focus on expecting the unexpected in models and theory.[14]

Risk Assessment

One method for incorporating uncertainty is to perform an expected value analysis. The expected value is simply the sum across all possible outcomes of the product of the probability of an outcome and the value (cost or benefit) of that outcome. Typically, modelers postulate two outcomes: a low-probability, high-damage case and a high-probability, low-damage case. However, this method is fraught with problems when applied to study climate change. First, expected value calculations assume risk neutrality and thus neglect any consideration of risk aversion, especially with respect to low-probability, catastrophic outcomes. A gambling analogy clarifies this concept. Suppose you are offered the following gamble: a 50 percent chance of winning $100 and a 50 percent chance of losing $100. The expected value, or average outcome, of this gamble is zero. Would you opt to take the gamble? If you were risk neutral, you would be indifferent between the two options. If you were risk averse, you would forgo the gamble, but if you were risk accepting, you would take your chances on the gamble. Risk neutrality implies indifference between receiving for certain the expected value across outcomes and accepting the single outcome from a one-time gamble across all possible outcomes. Risk aversion implies a preference for receiving the expected value over facing the gamble; in technical terms, the utility of the expected *value* of the gamble is greater than the expected *utility* of the gamble (Fig. 2.1). The difference between the expected value and the expected utility is the amount forgone to avoid facing the gamble—in other words, the risk premium.[15]

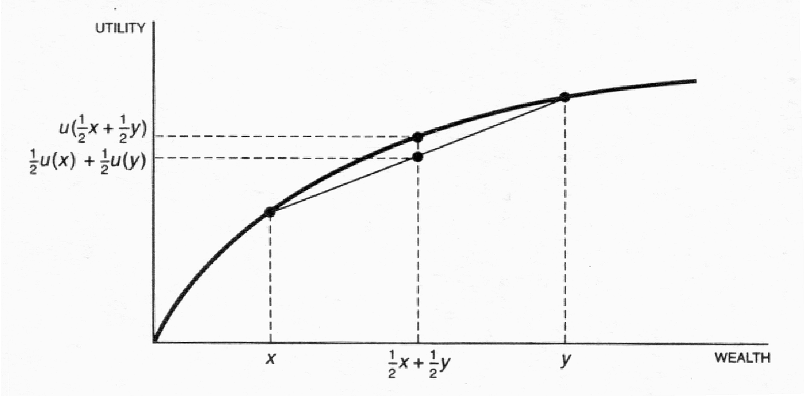

FIGURE 2.1. The expected utility of the gamble is 1/2U(X) + 1/2U(Y). The utility of the expected value of the gamble is U(1/2X + 1/2Y). In the risk averse case depicted the utility of the expected value is higher than the expected utility of the gamble. *Source:* Varian, 1992.

Imaginable Surprise

Strictly speaking, a surprise is an unanticipated outcome; by definition it is an unexpected event. Potential climate change and, more broadly, global environmental change are replete with this kind of surprise because of the enormous complexities of the processes and relationships involved (such as coupled ocean, atmosphere, and terrestrial systems) and our insufficient understanding of them.[16]

The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR),[17] defines "surprise" as rapid, nonlinear responses of the climatic system to anthropogenic forcing, such as the collapse of the "conveyor" belt circulation in the North Atlantic Ocean[18] or rapid deglaciation of polar ice sheets.

Unfortunately, most climate change assessments rarely consider low-probability, high-consequence events. Instead, assessments primarily consider scenarios that supposedly "bracket the uncertainty" rather than explicitly integrate unlikely events. Not even considered in the standard paradigm are structural changes in political or economic systems or changes in public consciousness regarding environmental issues. Although researchers recognize the wide range of uncertainty surrounding global climate change, their analyses are essentially surprise free.

Extreme events that are not truly unexpected are better defined as imaginable abrupt events. And for some surprises, although the outcome is unknown, it is possible to identify imaginable conditions for surprise to occur. For example, as the rate of change of CO_2 concentrations is one imaginable condition for surprise, the system would be less rapidly forced if decision makers chose to slow down the rate at which human activities modify the atmosphere. This would lower the likelihood of surprises. To deal with such questions, the policy community needs to understand both the potential for surprises and the difficulty of using current tools such as integrated assessment models (IAMs) to credibly evaluate the probabilities of currently imaginable "surprises," let alone those not currently envisioned.[19]

Incorporating Uncertainty and Surprise into IAMs of Climate Change

Climate Variability

A critical assumption of the standard assessment paradigm is whether the probability of climate extremes, such as droughts, floods, and super-hurricanes, will remain unchanged or will change with the mean change in climate according to unchanged variability distributions. As Mearns et al.[20] have shown, however, changes in the daily temperature variance or the autocorrelation of daily weather extremes can significantly reduce or dramatically exacerbate the vulnerability of agriculture, ecosystems, or other climate extreme–sensitive components of the environment to global warming. How such variability measures might change as the climatic mean changes is highly uncertain, although an increase in the number of extreme events with global warming is expected.[21] Variability in precipitation, most notably from an increase in high-intensity rainfall, is expected to increase. Karl and Knight[22] have observed that about half of the 8 percent increase in precipitation in the United States since 1910 occurred in the most damaging heavy downpours. In addition, the El Niño–Southern Oscillation (ENSO) could well continue the trend of the past two decades and become a more recurrent or stronger phenomenon, which will increase climate variability.[23]

Projections for storms (tropical cyclones, mid-latitude storms, tornadoes, and severe storms) are more controversial. Based on the assumption that wet bulb temperatures (a measure of the humidity of the atmosphere; the higher the humidity, the higher the temperature that a wet, i.e., evaporating, thermometer would measure) translate into larger potential energy for severe weather, recent studies have examined the link between temperature and extreme weather. Arguing that "storm activity may be more dependent on daily minimum temperatures than on daily maximums," Dessens[24] notes a positive correlation between nighttime temperatures and the frequency of severe storms (specifically hail storms in France) and projects a 40 percent increase in hail damage from a 1°C increase in mean minimum temperatures. Reeve and Toumi[25] note a link between lightning and temperature and predict a 40 percent ± 14 percent increase in lightning for a 1°C increase in wet bulb temperature. Currently, the climate record is too noisy to detect a clear signal of increased hurricane intensities, but the theoretical understanding of the driving forces behind hurricanes strongly suggests that peak intensities should be higher in a warmer world.[26] Although it is not possible to determine with high confidence, given current data and methods, the possibility of increased climate extremes from human disturbances is not remote.

Transient Effects of Climate Change

Standard assessments model responses to a one-time doubling of CO_2 and analyze the effects once the system reaches equilibrium. Clearly, what happens along the path to a new equilibrium is of interest as well, especially in the event of abrupt change. For example, resultant environmental or societal impacts are likely to be quite different from those that would occur with smoother, slower changes. The long-term impact of climate change may not be predictable solely from a single steady-state outcome but may well depend on the characteristics of the transient path. In other words, the outcome may be path dependent. Any exercise that neglects surprises or assumes transitivity of the earth system (i.e., a path-independent response) is indeed questionable and should carry a clear warning to users of the fundamental assumptions implicit in the technique dependent on steady state results. Furthermore, rapid transients and nonlinear events are likely to affect not only the mean values of key climate indicators but also higher statistical moments, such as variability, of the climate (e.g., week-to-week variability, seasonal highs and lows, and day-to-night temperature differences).

Rate of Forcing Matters

Even the most comprehensive coupled-system models are likely to have unanticipated results when forced to change very rapidly by external disturbances such as CO_2 and aerosols. Indeed, some of the transient coupled atmosphere–ocean models run out for hundreds of years exhibit dramatic change in the basic climate state.[27] Stocker and Schmittner[28] argue that rapid alterations in oceanic currents could be induced by faster rates of climate change. For very rapid increases in CO_2 concentrations, Thompson and Schneider[29] simulate a reversal of the equator-to-pole temperature difference in the Southern Hemisphere over the century immediately during and after the rapid buildup of CO_2. Slower increases in CO_2 would not create such a surprise. More recent research by Schneider and Thompson[30] suggests that factors contributing to a collapse of the THC in the North Atlantic Ocean include changes in the climate sensitivity, the overturning rate of the THC (i.e., how quickly cold, salty waters sink), the CO_2 stabilization level, and the rate of increase of CO_2 concentrations (the former two are uncertain biogeophysical factors and the latter two are social factors dependent on human decisions). Mastrandrea and Schneider show that the combination of these factors and the discount rate critically affect the “optimal” rate of CO_2 mitigation.[31] Furthermore, Schneider and Thompson demonstrate that abrupt and discontinuous environmental change can occur even when climate forcings are smooth.

Simulations by Schneider and Thompson[32] and Mastrandrea and Schneider[33] suggest that actions taken in the short term may have serious long-term, abrupt, potentially irreversible consequences. Mastrandrea and Schneider[34] demonstrate for some scenarios that only low discount rates stimulate sufficient controls on CO_2 emissions to prevent a circulation collapse, which implies that myopic policymakers may implement weak short-term climate policies that build into the long-term future unexpected, major changes in climatic conditions. To develop a climate policy that will lower the risk of climate catastrophes, policymakers need to consider consequences of climate change beyond the twenty-first century, including very uncertain but highly consequential events such as a THC collapse.

Estimating Climate Damages

A critical issue in climate change policy is costing climatic impacts, particularly when the possibility for nonlinearities, surprises, and irreversible events is allowed. The assumptions made when carrying out such estimations largely explain why different authors obtain different policy conclusions.

Subjective probability assessments of potential climate change impacts provide a crude metric for assigning dollar values to certain aspects of ecosystem services. We can anticipate costs associated with global change and place a preliminary value on some of the ecosystem services that could be affected. One way to assess the costs of climate change is to evaluate the historic losses from extreme climatic events, such as floods, droughts, and hurricanes.[35] Catastrophic floods and droughts are cautiously projected to increase in both frequency and intensity with a warmer climate and the influence of human activities such as urbanization, deforestation, aquifer depletion, groundwater contamination, and poor irrigation practices.[36] The financial service sector has taken particular note of the potential losses from climate change. Losses from weather-related disasters in the 1990s were eight times higher than in the 1960s. Although there is no clear evidence that hurricane frequency has changed over the past few decades (or will change in the next few decades), there is overwhelming data that damage from such storms has increased astronomically. Attribution of this trend to changes in socioeconomic factors (e.g., economic growth, population growth and other demographic changes, or increased penetration of insurance coverage) or to an increase in the occurrence or intensity of extreme weather events as a result of global climate change is uncertain and controversial. (Compare Vellinga et al.,[37] which acknowledges both social and climatic influences and recognizes the difficulty in attribution, to Pielke and Landsea,[38] which dismisses any effects of climate change.) Damage assessment is one possible way in which we can relate the cost of more inland and coastal flooding, droughts, and possible intensification of hurricanes to the value of preventing the disruption of climate stability.[39]

An assumption in cost–benefit calculations in the standard assessment paradigm is that “nature” is either constant or irrelevant. Because “nature” is beyond the purview of the market, cost–benefit analyses ignore its nonmarket value. For example, ecological services[40] such as pest control and waste recycling are omitted from most assessment calculations. Implicitly, this assumes that the economic value of ecological services is negligible or will remain unchanged with human disturbances. Recent assessments of the value of ecosystem services acknowledge the tremendous public good provided, not to mention the recreational and aesthetic value. For example, a cost assessment study in New York discovered that paying residents and farmers to reduce toxic discharges and other environmental disruptions to protect the Catskills, which provide a natural water purification service, produced a significant savings (on the order of billions of dollars) over building a new water treatment plant. Furthermore, it is highly likely that communities of species will be disrupted, especially if climate change occurs in the middle to upper range projected.[41]

The Discount Rate

Discounting plays a crucial role in the economics of climate change, yet it is a highly uncertain parameter. Discounting is a method of aggregating costs and benefits over a long time horizon by summing across future time periods net costs (or benefits) that have been multiplied by a discount rate, typically greater than zero. If the discount rate equals zero, then each time period is valued equally (case of infinite patience). If the discount rate is infinite, then only the current period is valued (case of extreme myopia). The discount rate chosen in assessment models is critical because abatement costs typically are incurred in the near term, but the brunt of climate damages is realized primarily in the long term. Thus, if the future is sufficiently discounted, present abatement costs will outweigh discounted future climate damages because discount rates will eventually reduce future damage costs to negligible present values.

Consider a climate impact that would cost $1 billion 200 years from now. A discount rate of 5 percent per year would make the present value of that future cost equal to $58,000. At a discount rate of 10 percent per year, the present value would be only $5. Changes in this parameter largely explain why some authors,[42] using large discount rates, conclude that CO_2 emission increases could be socially beneficial whereas others,[43] using low or zero discount rates, justify substantial emission reductions, even when using similar damage functions.[44]

It might seem that the appropriate discount rate is a matter of empirical determination, but the conflict involves a serious normative debate about how to value the welfare of future generations relative to current ones. Moreover, it requires that the current generation estimate what kinds of goods and services future generations will value (e.g., what trade-offs they will want to make between extra material wealth and greater loss of environmental services). Much of the debate centers around different interpretations of the normative implications of the choice of the discount rate.[45]

The descriptive approach chooses a discount rate based on observed market interest rates to ensure that investments are made in the most profitable projects. Supporters of this approach often argue that using a market-based discount rate is the most efficient way to allocate scarce resources used for competing priorities, of which one is mitigating the effects of climate change.

The prescriptive approach emphasizes that the choice of discount rate entails a choice on how the future should be valued. Proponents of intergenerational equity often argue that it is difficult to argue that the welfare of future generations should be discounted simply because they exist in the future.

Although these two approaches are the most common in IAMs of climate change, alternative discount methods have been proposed. There is empirical evidence to suggest that people exhibit hyperbolic discounting, in which discount rates decline over time with higher-than-market discount rates in the short run and lower discount rates over the long term.[46] This behavior is consistent with a common finding that "human response to a change in a stimulus is inversely proportional to the pre-existing stimulus."[47] Hyperbolic discounting can be derived from both the descriptive and the prescriptive approach, and is obtained when discount rates fall over time. This can be modeled in IAMs with a logarithmic discount factor[48] or by assuming that per capita income grows logistically over the next century; because the discount rate is proportional to growth rates, declining discount rates are obtained.[49]

Furthermore, if climate change is severe, such that future income falls rather than grows—growth is assumed in almost all IAMs—then the discount rate can be negative, provided that the rate of time preference is sufficiently low.[50] In this case, future welfare should be valued more than the present. The complexity in the discounting issue stems not only from uncertainty in how to calculate the value of the future once a discount rate is specified but also from uncertainty over whether any particular choice is appropriate for alternative value systems.

Agency

The predominant approach to the discounting problem is based on an infinitely lived representative agent (ILA) who maximizes utility from a future welfare stream subject to economic and environmental conditions, usually assumed to be known. The ILA framework imposes strong assumptions regarding intergenerational fairness.[51] An alternative modeling paradigm, the overlapping generations model (OLG), differentiates between individual time preference and intergenerational equity (the distinction is suppressed in the ILA model) and endogenizes the choice of discount rate.[52] A distinctive characteristic of OLG models (unlike ILA models in most IAMs) is that the OLG framework explicitly models the existence of generations who work and save when young and consume savings, or "dissave," when old. Thus, the two modeling frameworks represent different conceptions of intergenerational equity. The policy recommendations derived from the OGM differ fundamentally from those of the ILA model, including higher carbon emission abatement (however, Manne and Stephan[53] show that under certain restrictions, the results from the ILA and the OGM models concur).

Natural Variability Masks Trends and Delays Adaptation

One of the major differences in estimates of climatic impacts across different studies is how the impact assessment model treats adaptation of natural and human systems to climate change. For example, it has often been assumed that agriculture is the most vulnerable economic market sector to climate change. For decades agronomists have calculated potential changes in crop yields from various climate change scenarios, suggesting that some regions now too hot would sustain heavy losses from warming, whereas others, now too cold, could gain.[54] Rosenberg[55] has long argued that such agricultural impact studies implicitly invoke the "dumb farmer assumption." That is, they neglect the fact that farmers do adapt to changing market, technology, and climatic conditions. For example, Mendelsohn et al.[56] use cross-sectional analyses to estimate empirically the adaptation responses of real farmers to changes in climate (e.g., changes in crop yields and land rent values) by simply comparing land use activities in warm places such as the U.S. Southeast and colder places such as the Northeast as a proxy for how temperature changes might affect these segments of the economy. Agricultural economists such as John Reilly[57] argue that such adaptations will dramatically reduce the climate impact costs to market sectors such as farming, transportation, coastal protection, and energy use. However, ecologists and some social scientists often dispute this optimism. Haneman[58] notes that Mendelsohn et al. confound the normative statement that public policy *should* encourage efficient adaptation with the positive statement that adaptation *will be* efficient: "It is a large leap to go from the observation that there will be *some* adaptation to the inference that there will be *perfectly efficient* adaptation." Furthermore, Schneider[59] objects that the statistical analysis Mendelsohn et al. use ignores time-evolving or transient changes in temperature and other variables, not to mention surprises. In essence, they assume perfect substitutability for changes at one place over time with changes across space at the same time. Assuming a high level of adaptation neglects such real-world problems as resistance to trying unfamiliar practices, problems with new technologies, unexpected pest outbreaks,[60] or the high degree of natural variability of weather.

The high natural variability of climate probably will mask any slowly evolving anthropogenically induced climate trends, either real or forecasted. Furthermore, adaptation is likely to be a reaction to an already changed climate rather than a preemptive response to anticipated or projected climate change. Therefore, adaptations to slowly evolving trends embedded in a noisy background of inherent variability are likely to be delayed by decades behind the slowly evolving global change trends.[61] Moreover, were agents to mistake background variability for trend or vice versa, the possibility arises of adaptation following the wrong set of climatic cues. In particular, agents might be more influenced by regional anomalies of the recent past in projecting future trends. They may be unaware of the likelihood that very recent anomalous experience in one region may well be largely uncorrelated with slowly building long-term trends at a global scale or may be part of a transient response that will reverse later on. In addition, unwarranted complacency may result from the inability to foresee nonlinear events.

Passive Versus Anticipatory Adaptation

Schneider and Thompson,[62] in an intercomparison of climate change, ozone depletion, and acid rain problems, differentiate passive adaptation (e.g., buying more water rights to offset impacts of a drying climate) from anticipatory adaptation. They suggest, as a hedging strategy, investing in a vigorous research and development program for low-carbon energy systems in anticipation of the possibility of needing to reduce CO_2 emissions in the decades ahead. The idea is that it would be cheaper to switch to systems that were better developed as a result of such anticipatory investments. Such proactive forms of adaptation (e.g., building a dam a few meters higher in anticipation of an altered future climate) have been prominent in most subsequent formal assessments of anthropogenic climate change.[63] Nearly all modern integrated assessments explicitly[64] or implicitly[65] attempt to incorporate (mostly passive) adaptation. Although these studies should be applauded for attempting to recognize and evaluate the implications of adaptive responses on the impact costs of climate change scenarios, serious problems with data, theory, and method remain. In particular, analyses must incorporate a wide range of assumptions,[66] and both costs and benefits of climate change scenarios should be presented in the form of statistical distributions based on a wide range of subjective probability estimates of each step in the assessment process.[67]

Guidance on Uncertainties

Attempts to achieve more consistency in assessing and reporting on uncertainties are just beginning to receive increasing attention. However, the scientific complexity of the climate change issue and the need for information that is useful for policy formulation present a large challenge to researchers and policymakers alike; both groups must work together toward improved communication of uncertainties. The research community must also bear in mind that readers often assume for themselves what they think the authors believe to be the distribution of probabilities when the authors do not specify it themselves. For example, integrated assessment specialists may have to assign probabilities to alternative outcomes (even if only qualitatively specified by natural scientists) because many integrated assessment tools require estimates of the likelihood of a range of events to calculate efficient policy responses. Moss and Schneider[68] argue that it is more rational for experts to provide their best estimates of probability distributions and possible outliers than to have novice users make their own determinations. In particular, a guidance paper on uncertainties commissioned by the IPCC[69] recommends developing an estimate of a probability distribution based on the documented ranges and distributions in the literature, including sources of information on the key causes of uncertainty. An assessment should include a measure of the central tendency (if appropriate) of the distribution as well as a characterization of the end points of the range of outcomes and possible outliers—i.e., the likelihood of outcomes beyond the end points of the range. Truncating the estimated probability distribution should be avoided because this narrows the range of outcomes described and excludes outliers that may include "surprises" and does not convey to potential users a representation of the full range of uncertainty associated with the estimate. It is inappropriate to combine different distributions into one summary distribution if this obscures differences between two (or more) schools of thought. Representing the full distribution has important implications regarding the extent to which the analysis accurately conveys uncertainties.

A projected range is a quantifiable range of uncertainty situated within a population of possible futures that cannot be fully identified (nominated as "knowable" and "unknowable" uncertainties by Morgan et al.).[70] The limits of this total range of uncertainty are unknown but may be estimated subjectively.[71] The inner range represents a well-calibrated range of uncertainty based on doc

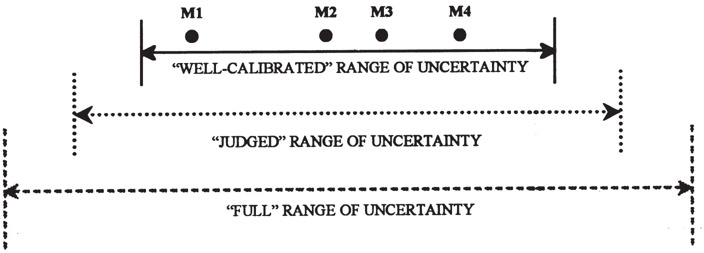

FIGURE 2.2. Schematic depiction of the relationship between "well-calibrated" scenarios, the wider range of "judged" uncertainty that might be elicited through decision analytic survey techniques, and the "full" range of uncertainty, which is drawn wider to represent overconfidence in human judgments. M1 to M4 represent scenarios produced by four models (e.g., globally averaged temperature increases from an equilibrium response to doubled CO_2 concentrations). This lies within a "full" range of uncertainty that is not fully identified, much less directly quantified by existing theoretical or empirical evidence. (Modified from Jones, 2000.)

umented literature. The wider range of uncertainty represents a "judged" range of uncertainty based on expert judgments, which may not encompass the full range of uncertainty given the possibility of cognitive biases such as overconfidence (Fig. 2.2). New information, particularly reliable and comprehensive empirical data, may eventually narrow the range of uncertainty by falsifying certain outlier values.

Aggregation and the Cascade of Uncertainty

A single aggregated damage function or a best-guess climate sensitivity estimate is a very restricted representation of the wide range of beliefs available in the literature or among lead authors, particularly because these estimates rely on a causal chain that includes several different processes. The resultant aggregate distribution might have very different characteristics than the various distributions that make up the links of the chain of causality.[72] Thus, poorly managed projected ranges in impact assessment may inadvertently propagate uncertainty. The process whereby uncertainty accumulates throughout the process of climate change prediction and impact assessment has been variously described as a cascade of uncertainty[73] or an uncertainty explosion.[74] The cascade of uncertainty implied by coupling the separate probability distributions for emissions, biogeochemical cycle calculations needed to calculate radiative forcing, climate sensitivity, climate impacts, and valuation of such impacts in climate damage functions has yet to be produced in the literature.[75] If an assessment is continued through to economic and social outcomes, even larger ranges of uncertainty can be accumulated (Fig. 2.3).

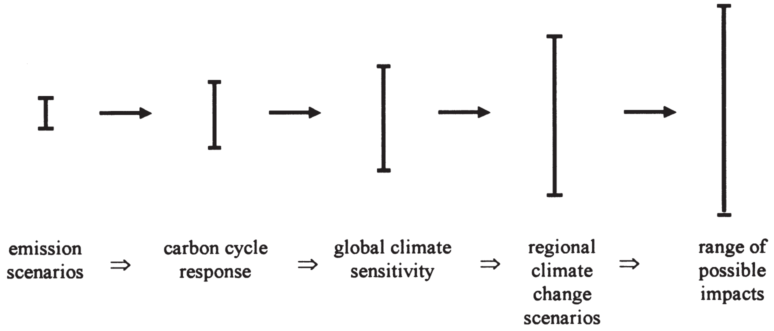

FIGURE 2.3. Range of major uncertainties typical in impact assessments showing the "uncertainty explosion" as these ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic, social, and political impacts and policy responses. (Modified after Jones, 2000 and the "cascading pyramid of uncertainties" in Schneider, 1983.)

This cascade of uncertainty produces a range of possible outcomes rather than best guesses.

Using Probability Distributions to Evaluate Climate Damage

Many recommendations for modest controls are based on point estimate values, that is, results that are derived from a series of best guesses. This point estimate method fails to account for the wide range of plausible values for many parameters. Similarly, output from a single model run does not display all the information available, nor does it offer sufficient information to provide the insights needed for well-informed policy decisions. Clearly, the use of probabilistic information, even if subjective, provides a much more representative picture of the broad views of the experts and a fairer representation of costs, which, in turn, allows better potential policy insights. The characterization and range of uncertainties of the information provided by decision analysis tools must be made explicit and transparent to policymakers.[76] Policymaking in the business, health, and security sectors often is based on hedging against low-probability but high-consequence outcomes. Thus, any climate policy analysis that represents best guess point values or limited ranges of outcomes limits the ability of policymakers to make strategic hedges against such risky outlier events. The end result of any set of integrated assessment modeling exercises will be the subjective choice of a decision maker,[77] but a more comprehensive analysis with uncertainties in all major components explicitly categorized and displayed should lead to a better-informed choice.[78]

Morgan and Keith[79] and Nordhaus[80] tap the knowledgeable opinions of what they believe to be representative groups of scientists from physical, biological, and social sciences on two separate questions: the climate science itself and policy-relevant impact assessment. In the Morgan and Keith study, 16 scientists were interviewed to elicit their subjective probability estimates for a number of factors, including the climate sensitivity factor (i.e., the increase in global mean temperature for a doubling of CO_2). The Morgan and Keith survey shows that although there is a wide divergence of opinion, nearly all scientists assign some probability of negligible outcomes and some probability of highly serious outcomes (Fig. 2.4).

Nordhaus[81] conducted a survey of conventional economists, environmental economists, atmospheric scientists, and ecologists to assess expert opinion on estimated climate damages. Interestingly, the survey reveals a striking cultural divide between natural and social scientists in the study. The most striking difference in the study is that conventional economists believe that even extreme climate change (i.e., 6°C warming by 2105) would not impose severe economic losses. Natural scientists' estimates of the economic impact of extreme climate change

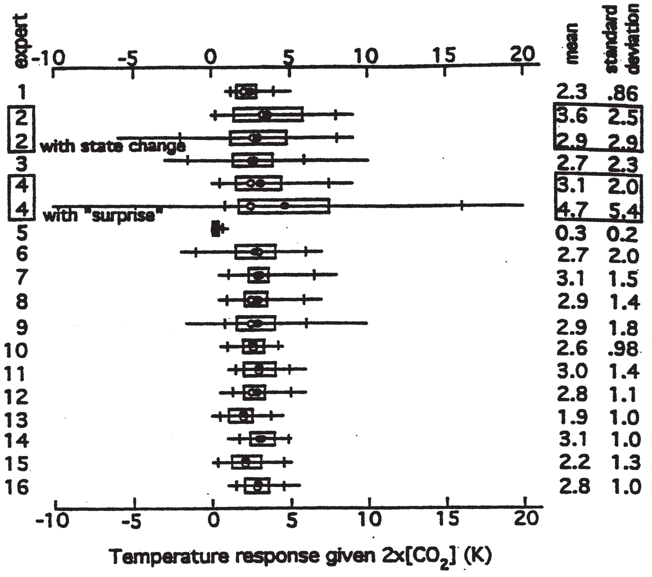

FIGURE 2.4. Box plots of elicited probability distributions of climate sensitivity, the change in globally averaged surface temperature for a doubling of CO_2 (2x[CO_2] forcing). Horizontal line denotes range from minimum (1%) to maximum (99%) assessed possible values. Vertical tick marks indicate locations of lower (5) and upper (95) percentiles. Box indicates interval spanned by 50% confidence interval. Solid dot is the mean and open dot is the median. The two columns of numbers on right hand side of the figure report values of mean and standard deviation of the distributions. (From Morgan & Keith, 1995.)

are 20 to 30 times higher than conventional economists'.[82] Despite the magnitude in difference of damage estimates between economists and ecologists, the shape of the damage estimate curve was similar. The respondents indicate accelerating costs with higher climate changes. Most respondents, economists and natural scientists alike, offer right-skewed subjective probability distributions. That is, most of the respondents consider the probability of severe climate damage ("nasty surprises") to be higher than the probability of moderate benefits ("pleasant surprises"). Roughgarden and Schneider[83] demonstrate that adopting such right-skewed probability distributions into integrated assessment models produces optimal carbon taxes several times higher than point estimates. The long, heavy tails of the skewed distribution (which Roughgarden and Schneider label "surprise") pull the median and means of the distribution away from the mode. Figure 2.5 shows this right skewness clearly for the Nordhaus survey.

We will not easily reconcile the optimistic and pessimistic views of these specialists with different training, traditions, and world views. One thing that is clear from the Morgan and Keith and the Nordhaus studies is that most knowledgeable experts from a variety of fields admit to a wide range of plausible outcomes in the area of climate change, including both mild and catastrophic outcomes. This condition is ripe for misinterpretation by those who are unfamiliar with the wide range of probabilities most scientists attach to climate change issues. The wide range of probabilities follows from recognition of the many uncertainties in data and assumptions still inherent in climate models, climatic impact models, economic models, or their synthesis via integrated assessment models.[84] In a highly interdisciplinary enterprise such as the integrated assessment of climate change, it is necessary to include a wide range of possible outcomes along with a

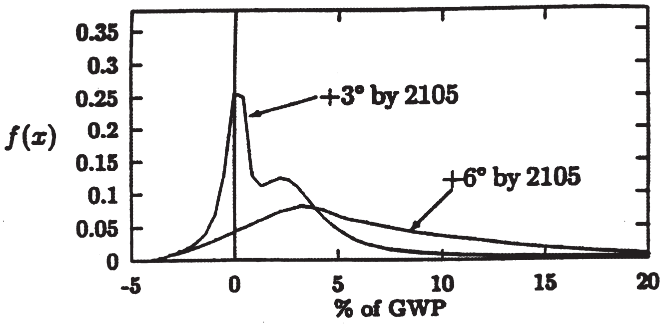

FIGURE 2.5. Probability distributions ($f(x)$) of climate damages as a percentage of gross world product (market and non-market components combined) from an expert survey in which respondents were asked to estimate 10th, 50th, and 90th percentiles for the two climate change scenarios shown. (From Roughgarden & Schneider, 1999. Data from Nordhaus, 1994a.)

representative sample of the subjective probabilities that knowledgeable assessment groups believe accompany each of those possible outcomes.

In essence, the "bottom line" of estimating climatic impacts is that extremely optimistic and pessimistic projections are the two lowest-probability outcomes (see Fig. 2.5) and that most knowledgeable scientists and economists consider there to be a significant chance of climatic damage to both natural and social systems. Under conditions of persistent uncertainty it is not surprising that most formal climatic impact assessments have called for cautious but positive steps to slow down the rate at which humans modify the climatic system and to make natural and social systems more resilient to whatever changes eventually materialize.[85]

Using Scenarios to Develop a Plausible Range of Outcomes

The IPCC commissioned a Special Report on Emission Scenarios (SRES)[86] both to broaden assessments to include a range of outcomes and to focus analysis on a coherent set of scenario outcomes to facilitate comparison. The scenarios concentrate on assumptions about economic growth, technological developments, and population growth, arguably the three most critical variables affecting the uncertainty over future climate change and policy options. To the extent possible, the Third Assessment Report (TAR)[87] has referred to the SRES to inform and guide the assessment. Box 2.2 describes the baseline SRES scenarios; Fig. 2.6 demonstrates how the SRES scenarios have been used to evaluate projected temperature changes.[88] However, IPCC did not assign subjective

BOX 2.2. The Emission Scenarios of the Special Report on Emission Scenarios (SRES)

A1: The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence between regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non–fossil energy sources (A1T), or a balance across all sources (A1B) (where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

BOX 2.2. *Continued*

A2: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines.

B1: The B1 storyline and scenario family describes a convergent world with the same global population (which peaks in midcentury and declines thereafter) as in the A1 storyline but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity but without additional climate initiatives.

B2: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population (at a rate lower than in A2), intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. Although the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1, and B2 represented in Fig. 2.6. The SRES authors consider the scenarios equally sound, which offers no guidance on which scenarios are more or less likely. A subjective probability assessment of the likelihood of the scenarios would offer policymakers a useful characterization of which scenarios may entail dangerous outcomes.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emission targets of the Kyoto Protocol or any next generation agreements.

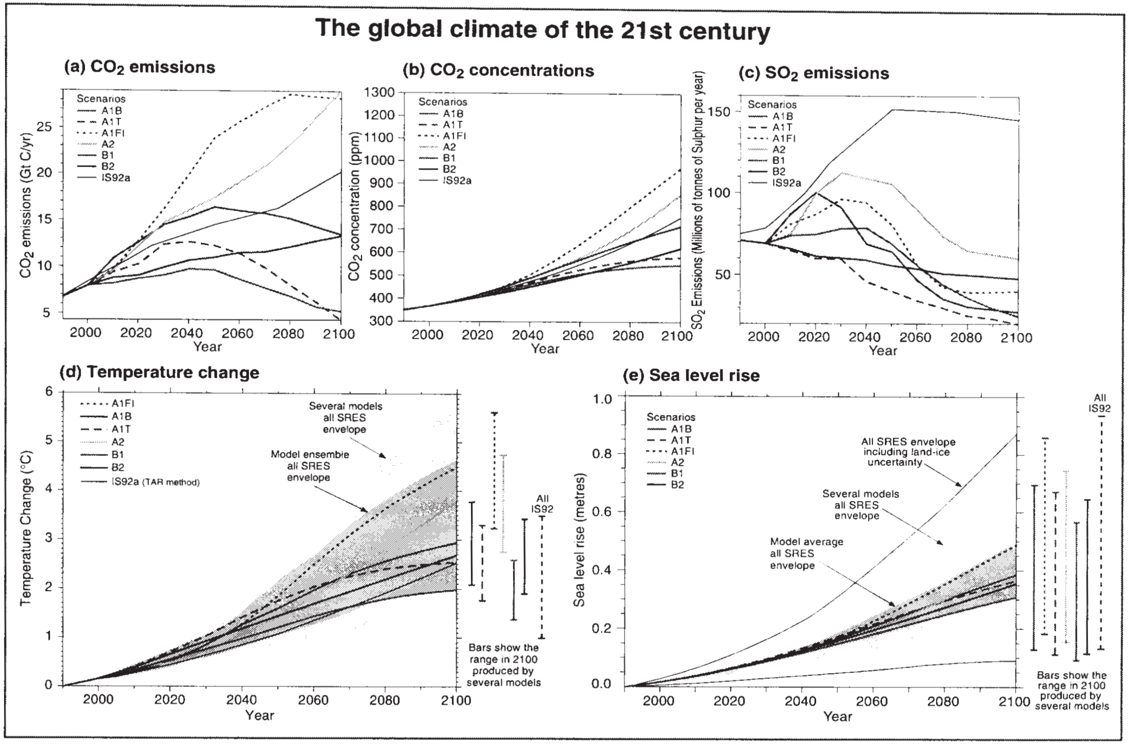

FIGURE 2.6. The global climate of the twenty-first century will depend on natural changes and the response of the climate system to human activities. Climate models project the response of many climate variables—such as increases in global surface temperature and sea level—to various scenarios of greenhouse gas and other human-related emissions. (a) CO_2 emissions of the six illustrative SRES scenarios, summarized Box 2.2, along with IS92a for comparison purposes with the SAR. (b) Projected CO_2 concentrations. (c) Anthropogenic SO_2 emissions. Emissions of other gases and other aerosols were included in the temperature change model but are not shown in the figure. (d), (e) The projected temperature and sea level responses, respectively. The "several models all SRES envelope" in (d) and (e) shows the temperature and sea level rise, respectively, for the simple model when tuned to a number of complex models with a range of climate sensitivities. The "all SRES envelopes" refer to the full range of 35 SRES scenarios. The "model average all SRES envelope" shows the average from these models for the range of scenarios. Note that the warming and sea level rise from these emissions would continue well beyond 2100. Also note that this range does not allow for uncertainty relating to ice dynamic changes in the West Antarctic ice sheet, nor does it account for uncertainties in projecting nonsulfate aerosols and greenhouse gas concentrations. (From IPCC, 2001a, Working Group I Summary for Policymakers, available online at http://www.ipcc.ch.)

probabilities to the SRES scenarios or to various climate model uncertainties, making it difficult for policymakers to compare risks or evaluate tradeoffs.[89]

Policy Implications

What Are Some Actions to Consider?

Given an uncertain environment with respect to our knowledge about the science of climate change, the impacts of climate change, and the effects of policy actions, what are reasonable policy options to mitigate or adapt to climate change? We suggest several options that collectively or separately will help to manage this uncertainty while assessing and addressing climate change.

Focus on Win–Win Strategies

Paramount is the need to pursue a climate policy with significant "co-benefits" that address other policy objectives. Despite the widespread agreement that at least some climatic change is inevitable, that major change is quite possible, and that most of the world will experience net effects that are more likely to be negative than positive, particularly if global warming is allowed to increase beyond a few degrees (which is likely to occur after the mid–twenty-first century if no policies are undertaken to mitigate emissions), many more pressing concerns critical to human health and well-being are competing for attention. Many countries are struggling to raise literacy rates, lower death rates, increase life expectancy, provide employment for burgeoning populations, and reduce local air and water pollution, which pose imminent health hazards to their citizens and environments. These demands are concrete, imminent, and vital to human welfare. In contrast, costs imposed by climate change often are diffuse, delayed, and intangible. Uncertainty about the consequences of climate change only exacerbates the problem. Slowing climate change is simply a low priority for many countries, even if it would be efficient to do so. It is unfortunate that less developed countries, in particular, place a low priority on the abatement of global climate change despite the fact that nearly all impact assessments suggest that it is these very countries that are most vulnerable to climatic change.[90] Furthermore, climate change probably will exacerbate these existing stresses. Policy responses to climate change, including both mitigation and adaptation, are more likely to succeed if they are linked to or integrated with policies designed to address nonclimatic stresses. Part of the assessment should include not only weighing competing risks and priorities against the costs of climate policy options but also considering how policies to address competing objectives may complement each other.

Understandably, policymakers place an emphasis on identifying no-regrets policies (measures that demonstrate positive net benefits) and co-benefits of climate policies (secondary benefits from climate policy options that also meet other policy objectives, such as reducing air and water pollution), both of which suggest linkages to other policy objectives. In addition to direct effects on problems other than greenhouse gas emissions, such as reducing air and water pollution, co-benefits of climate change policies may also include indirect effects on transportation, agriculture, land use practices, employment, and fuel security. Co-benefits may be experienced in the other direction as well; climate change mitigation may be an ancillary benefit of other policies. For example, a low greenhouse gas emission scenario could result from a sustainable development policy. Forest preservation is a particularly important, contemporary example of how accounting for co-benefits affects the value of policy options.

By current estimates, tropical deforestation accounts for 20 to 30 percent of carbon emissions. Clearly, protecting primary forests is a preferred global climate policy. However, conflicts between global, local, and national interests can undermine support for conservation. For example, the opportunity costs of the economic alternatives to the Masoala National Park Integrated Conservation and Development Program reveal that at the national level, industrial logging was the preferred option, despite the tremendous benefits of the conservation program to the local community (conservation yields local benefits greater than the slash-and-burn alternative).[91] It behooves the international community to support conservation efforts because of the tremendous *global* economic (and intrinsic) value of these forests. Paying national constituencies to preserve the Masoala forests would safeguard a valuable carbon sink at a low cost. Note that this is a value in addition—sometimes called a “double dividend”—to protecting biodiversity and ecosystem services. Despite the tremendous uncertainty regarding climate change and its implications for human welfare, all parties to the climate negotiations should recognize that potential damages to a global commons such as the earth’s climate are not mere ideological rhetoric. Policies to mitigate the effects of climate change are not cost free, but we should emphasize win–win solutions in which economic efficiency, cost-effectiveness, equity in the distributional impacts, and environmental protection can coexist.[92] Emphasizing the co-benefits of climate policy for other policy priorities can promote multiple objectives and secure support for mitigating climate change.[93]

Sensitivity Studies Are Essential

It is unlikely that all important uncertainties in either climatic or social and environmental impact assessment models will be resolved to the satisfaction of most of the scientific community in the near future. However, this does not imply that model results are uninformative. On the contrary, sensitivity analyses in which various policy-driven alternative radiative forcing assumptions are made and the consequences of these assumptions compared can offer insights into the potential effectiveness of such policies in terms of their differential climatic effects and impacts.[94] Even though absolute accuracy is not likely to be claimed for the foreseeable future, greater precision concerning the sensitivity of the physical and biological subsystems of the earth can be obtained via carefully planned and executed sensitivity studies across a hierarchy of models.

Validation and Testing Are Needed

Although it may be impractical, if not theoretically impossible, to validate the precise future course of climate given the uncertainties that remain in scenarios of emissions and land use changes, internal dynamics, and surprise events, many of the basic features of the coupled physical and biological subsystems of the earth already can be simulated. Testing models against each other when driven by the same sets of climate scenarios, testing the overall simulation skill of models against empirical observations, testing model parameterizations against high-resolution process models or data sets, testing models against proxy data of paleoclimatic changes, and testing the sensitivity of models to anthropogenic radiative forcings by computing their sensitivity to natural radiative forcings (e.g., seasonal radiative forcing, volcanic dust forcing, orbital element variation forcings, meltwater-induced rapid ocean current changes) make up a necessary set of validation-oriented exercises that all modelers should agree to perform. Impact assessment models should also be subjected to an analogous set of validation protocols (e.g., testing model projections against actual storm damage) to increase the credibility of their results. Similarly, economic models can be tested to see how they perform when simulating such shocks as the OPEC oil embargoes or the free trade agreements implementation. Further analysis should focus on systematically extending and evaluating existing assessment models to gauge the range of outcomes and their sensitivity to a variety of specification assumptions.

Finally, the most complex and difficult testing challenge is to fashion methods to test the behavior of emergent properties of coupled physical, biological, and social scientific submodels because the behavior of such highly integrated socioecological models is what most matches the complexity of the world we live in. The best suggestion we can offer here is that a hierarchy of models of increasing complexity be compared first against each other and then against data at as many scales as possible.[95] As the hierarchy is expanded and more testing protocols implemented, the confidence of the scientific community in the credibility of such modeling of the dynamics of the socioecological system will increase.

Incorporate Subjective Probability Assessment

In addition to standard simulation modeling exercises in which various parameters are specified or varied over an uncertainty range, formal decision analytic techniques can be used to provide a more consistent set of values for uncertain model parameters or functional relationships.[96] The embedding of subjective probability distributions into climatic models is just beginning[97] but may become an important element of integrated assessment modeling in future generations of model building.[98]

Provide for "Rolling Reassessment"

Changes in environmental and societal systems and our understanding of them will certainly occur over the next few decades. Under these circumstances, flexible management of global commons such as the earth's climate seems necessary to incorporate new discoveries. Therefore, a series of assessments of climatic effects, related impacts, and policy options to prevent potentially dangerous impacts will be needed periodically—perhaps every five years, as IPCC has chosen for the repeat period of its major Assessment Reports, which consider climatic effects, impacts, and policy issues. Whatever policy instruments are used (either mitigative or adaptive) must be flexible enough to respond quickly and cost-effectively to the evolving science that will emerge from this rolling reassessment process.

Some politicians are reluctant to revisit politically contentious issues every five years or so and prefer to "solve" them once and for all. Although that is a politically more palatable strategy for some, it is certain to be less efficient than flexible management given the high probability that new information will reduce some risks currently believed to be potentially serious and elevate others not now perceived as dangerous. Learning to live with changing assessments and flexible management instruments will be a hallmark of environmental debates in the twenty-first century.

Consider Surprises and Irreversibility

Given the many uncertainties that still attend most aspects of the climate change debate, priority should be given to the aspects that could exhibit irreversible damages (e.g., extinction of species whose already-shrinking habitat is further stressed by rapid climatic changes) or for which imaginable "surprises"[99] have been identified (e.g., changes in oceanic currents caused by rapid increases in greenhouse gases).[100] For these reasons, management of climatic risks must be considered well in advance of more certain knowledge of climatic effects and impacts.

Promote Environmentally Friendly Technologies

Schneider and Goulder[101] show that current policy actions, such as imposing a moderate carbon tax, are urgently needed to induce the technological innovations assumed in economic cost-effectiveness studies. In other words, policy actions to help induce technological changes (e.g., through research and development or "learning by doing") are needed now to promote cost-effective abatement in the decades ahead.[102]

Controversy will remain, of course, because total emissions are the product of world population size, per capita economic output, and the activities that produce that economic output. Technological innovations to reduce emissions are less controversial than social policies, which affect factors such as population and economic growth or consumption patterns. Thus, incentives for technology development and deployment are likely to be the focus of climate policy for the immediate future. Social factors eventually will need to be considered if very large human impacts on the environment are to be averted.[103]

Consider Carbon Management Alternatives

Two broad classes of carbon management can be distinguished. The first includes attempts to manipulate natural biogeochemical processes of carbon removal—so-called carbon sinks—such as adding iron to the oceans to enhance uptake of carbon by the resulting blooms of phytoplankton, planting vast forests of fast-growing trees to sequester carbon, or altering agricultural practices to increase carbon storage in soils.[104] The second kind of carbon management stresses prevention of carbon emissions that otherwise would have been directly injected into the atmosphere, including preservation of primary forests that otherwise might have been cut down (also helping to preserve biodiversity); industrial processing to increase the hydrogen content and remove carbon from fuels such as coal or methane, injecting the carbon into (hopefully stable) reservoirs for long-term storage; and using less carbon-intensive energy supply systems and improving energy efficiency. Keith[105] suggests that the dividing line between geoengineering (carbon management through deliberate modification of biogeochemical cycles) and mitigation (carbon management through prevention of carbon emission release to the atmosphere) occurs when the technology acts by counterbalancing an anthropogenic forcing rather than by reducing it.

Conclusions

We have argued that nonlinearities and the likelihood of rapid, unanticipated events ("surprises") require that integrated assessment methods use a wide range of estimates for key parameters or structural formulations and that, when possible, results be cast in probabilistic terms rather than central tendencies because the latter mask the wide range of policy relevant results. We have also argued that the underlying structural assumptions and parameter ranges be explicit to make the conclusions as transparent as possible. For example, although it is often acknowledged that a wide range of uncertainty accompanies estimates of climate damages from scenarios of anthropogenic climatic change (because of uncertainties in adaptation capacity, synergistic impacts, and so on), it is less common[106] to have a comparably wide set of estimates for mitigation costs of carbon policies (e.g., a carbon tax being a common analytic benchmark). Yet the tighter range of mitigation cost estimates occurs in part because standard costing methods make common assumptions about the lack of preexisting market failures or do not explicitly account for the possibility of climate policy–induced technological changes reducing mitigation cost estimates.[107]

Moreover, in view of the wide range of plausible climatic change scenarios available in the literature—including a growing number of rapid non-linear change projections—it is important for costing analyses to consider many such scenarios, including the implications of rapid changes in emissions triggering nonlinear climatic changes with potentially significant implications for costing.[108]

In short, the key is transparency of assumptions and the use of as wide a range of eventualities (and their attendant probabilities) as possible to help decision makers become aware of the arguments for flexibility of policy options.

Acknowledgments

This chapter is modified from Schneider, Turner, and Morehouse Garriga; Schneider, 2002b;[109] and Schneider et al., 2000.[110] We gratefully acknowledge the comments by Robert van der Zwan.

We also gratefully acknowledge the partial support of the Winslow Foundation, which has made this contribution possible.

Kristin Kuntz–Duriseti is in the department of political science at the University of Michigan and is also associated with the Institute for International Studies and Biological Sciences at Stanford University. She gratefully acknowledges support from the Winslow Foundation for part of this effort.

Notes

1. Farman, J. C., B. G. Gardiner, and J. D. Shanklin, 1985: "Larger losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction," *Nature,* 315: 207–210.
2. For example, Root, T. L. and S. H. Schneider, 1993: "Can large-scale climatic models be linked with multiscale ecological studies?" *Conservation Biology,* 7 (2): 256–270.
3. Intergovernmental Panel on Climate Change (IPCC), 2000: *Special Report: Emissions Scenarios (SRES)*, Nakicenovic, N., et al. (eds.), A Special Report of Working Group III of the IPCC (Cambridge, England: Cambridge University Press), 599 pp., available online: http://www.ipcc.ch.
4. IPCC, 1996a: *Climate Change 1995: The Science of Climate Change*, contribution of Working Group I to the Second Assessment Report of the IPCC, Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.) (Cambridge, England: Cambridge University Press), 572 pp.; IPCC, 2001a: *Climate Change 2001: The Scientific Basis*, contribution of Working Group I to the Third Assessment Report of the IPCC, Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu (eds.) (Cambridge, England: Cambridge University Press), 881 pp.
5. IPCC, 2001b: *Climate Change 2001: Impacts, Adaptations, and Vulnerability*, contribution of Working Group II to the Third Assessment Report of the IPCC, McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, K. S. White (eds.) (Cambridge, England: Cambridge University Press), 1032 pp.
6. Smith, J. and D. Tirpak (eds.), 1988: *The Potential Effects of Global Climate Change on the United States: Draft Report to Congress.* Vols. 1 and 2. U.S. Environmental Protection Agency, Office of Policy Planning and Evaluation, Office of Research and Development (Washington, DC: U.S. Government Printing Office); IPCC, 1996b: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analyses*, contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. R. T. Watson, M. C. Zinyowera, and R. H. Moss (eds.) (Cambridge, England: Cambridge University Press), 878 pp; IPCC, 2001b.
7. Nordhaus, W. D., 1994a: "Expert opinion on climatic change," *American Scientist* (January issue), 82: 45–52.
8. For example, Brown, P., 1997: "Stewardship of climate," an editorial for *Climatic Change,* 37 (2): 329–334.
9. Wynne, B., 1992: "Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm," *Global Environmental Change,* 20: 111–127; quote on p. 111.
10. From Moss, R. H. and S. H. Schneider, 2000: "Uncertainties in the IPCC TAR: recommendation to lead authors for more consistent assessment and reporting," in R. Pachauri, T. Taniguchi, and K. Tanaka (eds.), *Third Assessment Report: Cross Cutting Issues Guidance Papers* (Geneva: World Meteorological Organisation), pp. 33–51. Available on request from the Global Industrial and Social Progress Institute at http://www.gispri.or.jp.

11. Holling, C. S., 1973: "Resilience and stability of ecological systems," *Annual Review of Ecology and Systematics,* 4: 1–23; Holling, C. S., 1986: "The resilience of terrestrial ecosystems: local surprise and global change," in W. C. Clark and R. E. Munn (eds.), *Sustainable Development of the Biosphere* (Cambridge, England: Cambridge University Press for the International Institute for Applied Systems Analysis), pp. 292–317.
12. For example, see Ayyub, B. M., M. M. Gupta, and L. N. Kanal (eds.), 1992: *Analysis and Management of Uncertainty: Theory and Applications* (Amsterdam: North-Holland Publishers), 428 pp; Tonn, B., 1991: "Research policy and review 34: the development of ideas of uncertainty representation," *Environment and Planning,* 23: 783–812; Yager, R. R., 1992: "Decision making under Dempster–Shafer uncertainty," *International Journal of General Systems,* 20: 233–245.
13. For example, Zadeh, L. A., 1965: "Fuzzy sets," *Information and Control,* 8 (3): 338–353; Zadeh, L. A., 1990: "The birth and evolution of fuzzy logic," *International Journal of General Systems,* 17: 95–105.
14. For example, Casti, J. L., 1994: *Complexification: Explaining a Paradoxical World Through the Science of Surprise* (New York, Harper Collins), 320 pp.
15. See any undergraduate microeconomics textbook for a fuller exposition, e.g., Varian, H., 1992: *Intermediate Microeconomics,* 3rd ed. (New York: W. W. Norton), 506 pp.
16. For example, Chapter 1 and Summary for Policymakers, IPCC, 1996a; Casti, 1994; Darmstadter, J. and M. A. Toman (eds.), 1993: *Assessing Surprises and Nonlinearities in Greenhouse Warming. Proceedings of an Interdisciplinary Workshop* (Washington, DC: Resources for the Future); Broecker, W. S., 1994: "Massive iceberg discharges as triggers for global climate change," *Nature,* 372 (1): 421–424.
17. See IPCC, 1996a, p 7.
18. Rahmstorf, S., 2000: "The thermohaline ocean circulation: a system with dangerous thresholds? An editorial comment," *Climatic Change,* 46 (3): 247–256.
19. For discussions and a review of the literature, see Schneider, S. H., B. L. Turner, and H. Morehouse Garriga, 1998: "Imaginable surprise in global change science," *Journal of Risk Research,* 1 (2): 165–185.
20. Mearns, L. O., R. W. Katz, and S. H. Schneider, 1984: "Extreme high temperature events: changes in their probabilities and changes in mean temperature," *Journal of Climate and Applied Meteorology,* 23: 1601–1613.
21. See IPCC, 2001a.
22. Karl, T. R., and R. W. Knight, 1998: "Secular trends of precipitation amount, frequency, and intensity in the U.S.A.," *Bulletin of the American Meteorological Society,* 79 (2): 231–241.
23. See IPCC, 2001b.
24. Dessens, J., 1995: "Severe convective weather in the context of a nighttime global warming," *Geophysical Research Letters,* 22 (10): 1241–1244.
25. Reeve, N. and R. Toumi, 1999: "Lightning activity as an indicator of climate change," *Quarterly Journal of the Royal Meteorological Society,* 125: 893–903.
26. Emanuel, K. A., 1987: "The dependence of hurricane intensity on climate," *Nature,* 326: 483–485; Walsh, K. and A. B. Pittock, 1998: "Potential changes in tropical

storms, hurricanes, and extreme rainfall events as a result of climate change," *Climatic Change,* 39: 199–213; IPCC, 2001b.

27. Several authors examine possible radical changes in global ocean currents, such as Manabe S., and R. J. Stouffer, 1993: "Century scale-effects of increased atmospheric CO_2 on the ocean–atmosphere system," *Nature,* 364: 215–218; Haywood, J. M., R. J. Stouffer, R. T. Wetherald, S. Manabe, and V. Ramaswamy, 1997: "Transient response of a coupled model to estimated changes in greenhouse gas and sulfate concentrations," *Geophysical Research Letters,* 24 (11): 1335–1338; Rahmstorf, S., 1999: "Shifting seas in the greenhouse?" *Nature,* 399: 523–524.
28. Stocker, T. F. and A. Schmittner, 1997. "Influence of CO_2 emission rates on the stability of the thermohaline circulation," *Nature,* 388: 862–864.
29. Thompson, S. L. and S. H. Schneider, 1982: "CO_2 and climate: the importance of realistic geography in estimating the transient response," *Science,* 217: 1031–1033.
30. Schneider, S. H. and S. L. Thompson, 2000. "A simple climate model used in economic studies of global change," in S. J. DeCanio, R. B. Howarth, A. H. Sanstad, S. H. Schneider, and S. L. Thompson, *New Directions in the Economics and Integrated Assessment of Global Climate Change* (Washington, DC: The Pew Center on Global Climate Change), pp. 59–80.
31. Mastrandrea, M. and S. H. Schneider, 2001: "Integrated assessment of abrupt climatic changes," *Climate Policy,* 1: 433–449.
32. Schneider and Thompson, 2000.
33. Mastrandrea and Schneider, 2001.
34. Ibid.
35. Alexander, S. E., S. H. Schneider, and K. Lagerquist, 1997: "The interaction of climate and life," in G. C. Daily (ed.), *Nature's Services: Societal Dependence on Natural Ecosystems* (Washington, DC: Island Press), pp. 71–92.
36. IPCC, 1996a, 2001b.
37. Vellinga, P., E. Mills, G. Berz, S. Huq, L. Kozak, J. Palutikof, B. Schanzenbächer, S. Shida, and G. Soler, 2001. "Insurance and other financial services," in IPCC 2001b, pp. 417–450.
38. Pielke, R. A., Jr., and C. W. Landsea, 1998: "Normalized hurricane damages in the United States, 1925–97," *Weather Forecasting,* 13: 351–361.
39. For example, see Alexander et al., 1997; Titus, J. and V. Narayanan, 1996: "The risk of sea level rise: A Delphic Monte Carlo analysis in which twenty researchers specify subjective probability distributions for model coefficients within their respective areas of expertise," *Climatic Change,* 33 (2): 151–212; Yohe, G., J. Neumann, P. Marshall, and H. Ameden, 1996: "The economic cost of greenhouse induced sea level rise for developed property in the United States," *Climatic Change,* 32 (4): 387–410; Yohe, G., 1989: "The cost of not holding back the sea: economic vulnerability," *Ocean and Shoreline Management,* 15: 233–255.
40. Daily, G. C., 1997: *Nature's Services: Societal Dependence on Natural Ecosystems* (Washington, DC: Island Press), 392 pp.
41. Root, T. L. and S. H. Schneider, 1993: "Can large-scale climatic models be linked with multiscale ecological studies?" *Conservation Biology,* 7 (2): 256–270; Root, T. L. and S. H. Schneider, 2002: "Climate change: Overview and implications for

wildlife," in Schneider, S. H. and T. L. Roots (eds.), *Wildlife Responses to Climate Change: North American Case Studies,* National Wildlife Federation, (Washington, DC: Island Press), pp 1–55.

42. Nordhaus, W. D., 1994b: *Managing the Global Commons: the Economics of Climate Change* (Cambridge, MA: MIT Press); Manne, A. S., R. Mendelsohn, and R. G. Richels, 1995: "MERGE: a model for evaluating regional and global effects of GHG reduction policies," *Energy Policy,* 23: 17–34.
43. Cline, W., 1992: *The Economics of Global Warming* (Washington, DC: Institute of International Economics), 399 pp; Azar, C. and T. Sterner, 1996: "Discounting and distributional considerations in the context of climate change," *Ecological Economics,* 19: 169–185; Hasselmann, K., S. Hasselmann, R. Giering, V. Ocaña, and H. von Storch, 1997: "Sensitivity study of optimal CO_2 emission paths using a simplified structural integrated assessment model (SIAM)," *Climatic Change,* 37 (2): 345–386; Schultz P. A. and J. F. Kasting, 1997: "Optimal reductions in CO_2-emissions," *Energy Policy,* 25: 491–500; Mastrandrea and Schneider, 2001; Lind, R. C. (ed.), 1982: *Discounting for Time and Risk in Energy Policy* (Washington, DC: Resources for the Future), pp. 257–271.
44. For an overview of the discounting debate, see discussion in Portney, P. R. and J. P. Weyant (eds.), 1999: *Discounting and Intergenerational Equity* (Washington, DC: Resources for the Future), 186 pp.
45. Arrow, K. J., W. Cline, K. G. Mäler, M. Munasinghe, R. Squitieri, and J. Stiglitz, 1996: "Intertemporal equity, discounting and economic efficiency," in J. P. Bruce, H. Lee, and E. F. Haites (eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change. Second Assessment of the Intergovernmental Panel on Climate Change* (Cambridge, England: Cambridge University Press), pp. 125–144; Nordhaus, W. D., 1997: "Discounting in economics and climate change" (editorial), *Climatic Change,* 37 (2): 315–328; Markandya, A. and K. Halsnaes, 2000: "Costing methodologies," in R. Pachauri, T. Taniguchi, and K. Tanaka (eds.), *The Third Assessment Report: Cross Cutting Issues Guidance Papers* (Geneva: World Meteorological Organization), pp. 15–31. Available on request from the Global Industrial and Social Progress Institute at http://www.gispri.or.jp.
46. Ainslie, G., 1991: "Derivation of 'rational' economic behaviour from hyperbolic discount curves," *American Economic Association Papers and Proceedings,* 81 (2): 334–340.
47. Heal, G., 1997. "Discounting and climate change, an editorial comment," *Climatic Change,* 37 (2): 335–343, quote on page 339.
48. Ibid.
49. Azar, C. and T. Sterner, 1996; Portney and Weyant, 1999.
50. Azar, C. and O. Johansson, 1996: *Uncertainty and Climate Change—or the Economics of Twin Peaks,* presented at the annual conference of European Environmental and Resource Economists, June 1996, Lisbon.
51. Solow, R. M., 1974a: "Intergenerational equity and exhaustible resources," *Review of Economic Studies* (Symposium), 29–45; Solow, R. M., 1974b. "The economics of resources or the resources of economics," *American Economic Review,* 64 (2): 1–14; Lind, 1982; Richard Howarth, personal communication, 2000.

52. Howarth, R. B., 2000: “Climate change and international fairness,” in S. J. DeCanio, R. B. Howarth, A. H. Sanstad, S. H. Schneider, and S. L. Thompson, *New Directions in the Economics and Integrated Assessment of Global Climate Change* (Washington, DC: The Pew Center on Global Climate Change), pp. 43–58; Gerlagh, R. and B. C. C. van der Zwaan, 2001: “The effects of aging and an environmental trust fund in an overlapping generations model on carbon emission reductions,” *Ecological Economics,* 36 (2): 311–326.
53. Manne, A. S. and G. Stephan, 1999: “Climate-change policies and intergenerational rate-of-return differentials,” *Energy Policy,* 27 (6): 309–316.
54. For example, see references in Rosenzweig, C. and M. Parry, 1994: “Potential impact of climate change on world food supply,” *Nature,* 367: 133–138; Smith and Tirpak, 1988.
55. Rosenberg, N. J. and M. J. Scott, 1994: “Implications of policies to prevent climate change for future food security,” *Global Environmental Change,* 4: 49–62.
56. Mendelsohn, R., W. Nordhaus, and D. Shaw, 1994: “The impact of global warming on agriculture: a Ricardian analysis,” *The American Economic Review,* 84 (4): 753–771.
57. Reilly, J., W. Baethgen, F. E. Chege, S. C. van de Geijn, L. Erda, A. Iglesias, G. Kenny, D. Patterson, J. Rogasik, R. Rötter, C. Rosenzweig, W. Sombroek, J. Westbrook, D. Bachelet, M. Brklacich, U. Dämmgen, M. Howden, R. J. V. Joyce, P. D. Lingren, D. Schimmelpfennig, U. Singh, O. Sirotenko, and E. Wheaton, 1996. “Agriculture in a changing climate: impacts and adaptation,” in R. T. Watson, M. C. Zinyowera, and R. H. Moss (eds.), Intergovernmental Panel on Climate Change (IPCC), 1996: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analyses*, contribution of Working Group II to the Second Assessment Report of the IPCC (Cambridge, England: Cambridge University Press), pp. 427–467.
58. Haneman, W. M., 2000: “Adaptation and its measurement. An editorial comment,” *Climatic Change,* 45 (3–4): 571–581; quote on p. 575.
59. Schneider, S. H., 1997: “Integrated assessment modeling of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions?” *Environmental Modeling and Assessment,* 2 (4): 229–248.
60. Ehrlich, P. R., A. H. Ehrlich, and G. Daily, 1995: *The Stork and the Plow* (New York: Putnam).
61. For example, Kaiser, H. M., S. Riha, D. Wilks, D. Rossiter, and R. Sampath, 1993: “A farm-level analysis of economic and agronomic impacts of gradual climate warming,” *American Journal of Agricultural Economics,* 75: 387–398; Schneider, S. H., 1996: “The future of climate: potential for interaction and surprises,” in T. E. Downing (ed.), *Climate Change and World Food Security* (Heidelberg: Springer-Verlag), NATO ASI Series 137: 77–113; Morgan, G. and H. Dowlatabadi, 1996: “Learning from integrated assessment of climate change,” *Climatic Change,* 34 (3–4): 337–368; Kolstad, C. D., D. L. Kelly, and G. Mitchell, 1999: *Adjustment Costs from Environmental Change Induced by Incomplete Information and Learning,* Department of Economics, UCSB Working Paper; Schneider, S. H., W. E. Easter-

ling, and L. Mearns, 2000: "Adaptation: Sensitivity to natural variability, agent assumptions and dynamic climate changes," *Climatic Change,* 45 (1): 203–221.

62. Schneider, S. H. and S. L. Thompson, 1985. "Future changes in the atmosphere," in R. Repetto (ed.), *The Global Possible* (New Haven, CT: Yale University Press), pp. 397–430.
63. For example, National Academy of Sciences (NAS), 1991: *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base.* Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy (Washington, DC: National Academy Press).
64. For example, Rosenberg, N. J. (ed.), 1993: "Towards an integrated impact assessment of climate change: The MINK study," *Climatic Change* (Special Issue), 24: 1–173; Rosenzweig and Parry, 1994; Reilly et al., 1996.
65. For example, Mendelsohn et al., 1994; Mendelsohn, R., W. Nordhaus, and D. Shaw, 1996: "Climate impacts on aggregate farm value: accounting for adaptation," *Agricultural and Forest Meteorology,* 80: 55–66; Mendelsohn, R., W. Morrison, M. Schlesinger, and N. Andronova, 2000: "Country-specific market impacts of climate change," *Climatic Change,* 45 (3–4): 553–569.
66. For example, as recommended by Carter, T. R., M. L. Parry, H. Harasawa, and S. Nishioka, 1994: *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. Summary for Policy Makers and a Technical Summary* (London: Department of Geography, University College London, and the Center for Global Environmental Research, National Institute for Environmental Studies, Japan), 59 pp.
67. For example, as advocated by Yohe, G. W., 1991: "Uncertainty, climate change, and the economic value of information: an economic methodology for evaluating the timing and relative efficacy of alternative response to climate change with application to protecting developed property from greenhouse induced sea level rise," *Policy Science,* 24 (3): 245–269; Morgan and Dowlatabadi, 1996; Schneider, 1997.
68. Moss and Schneider, 2000; see also Moss, R. H., 2000: "Cost estimation and uncertainty," *Pacific and Asian Journal of Energy,* 10 (1): 43–62.
69. Moss and Schneider, 2000.
70. Morgan, M. G., M. Henrion, and M. Small, 1990: *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* (New York: Cambridge University Press).
71. Morgan, M. G. and D. W. Keith, 1995: "Subjective judgments by climate experts," *Environmental Science and Technology,* 29: 468A–476A; Nordhaus, 1994a.
72. Modified from Jones, R. N., 2000: "Managing uncertainty in climate change projections–Issues for impact assessment, an Editorial Comment," *Climate Change,* 45 (3–4): 403–419.
73. Schneider, S. H., 1983: "CO_2, climate and society: a brief overview," in R. S. Chen, E. Boulding, and S. H. Schneider (eds.), *Social Science Research and Climate Change: An Interdisciplinary Appraisal* (Boston: D. Reidel), pp. 9–15.
74. Henderson-Sellers, A., 1993: "An Antipodean climate of uncertainty," *Climatic Change,* 25: 203–224.
75. See Table 2 in Schneider, 1997.

76. Moss, R. and S. H. Schneider, 1997: "Characterizing and communicating scientific uncertainty: moving ahead from the IPCC second assessment," in S. J. Hassol and J. Katzenberger (eds.), *Elements of Change 1996* (Aspen, CO: Aspen Global Change Institute), pp. 90–135; Moss and Schneider, 2000.
77. Schneider, 1997.
78. For example, Titus and Narayanan, 1996, combine climate models with expert subjective opinion to derive a statistical distribution for future sea level rise, and Morgan and Dowlatabadi, 1996, present a probability distribution comparing CO_2 emission abatement costs with averted climate damages.
79. Morgan and Keith, 1995.
80. Nordhaus, 1994a.
81. Ibid.
82. Ibid.; Roughgarden, T. and S. H. Schneider, 1999: "Climate change policy: quantifying uncertainties for damages and optimal carbon taxes," *Energy Policy,* 27 (7): 415–429.
83. Ibid.
84. Schneider, 1997.
85. For example, NAS, 1991.
86. IPCC, 2000.
87. IPCC, 2000a, 2000b; Intergovernmental Panel of Climatic Change (IPCC), 2001c: *Climate Change 2001: Mitigation,* contribution of Working Group III to the Third Assessment Report of the IPCC on Climate Change, Metz, B., O. Davidson, R. Swart, and J. Pan (eds.) (Cambridge, England: Cambridge University Press), 752 pp.
88. IPCC, 2001a.
89. For example, see Schneider, S. H., 2001a: "What is 'dangerous' climate change?" *Nature,* 411 (May 3): 17–19, and the rebuttal by Grübler, A. and N. Nakicenovic, 2001: "Identifying dangers in an uncertain climate," *Nature,* 412 (July 5): 15, and the perspective by Pittock, A. B., R. N. Jones, C. D. Mitchell, 2001: "Probabilities will help us plan for climate change," *Nature,* 413, p. 249. See also the later rebuttal: Schneider, S. H., 2002: Editorial Comment: "Can we estimate the likelihood of climatic changes at 2100?" *Climatic Change*, 52 (4): 441–451.
90. For example, Rosenzweig and Parry, 1994; IPCC, 2001b.
91. Kremen, C., J. O. Niles, M. G. Dalton, G. C. Daily, P. R. Ehrlich, J. P. Fay, D. Grewal, and R. P. Guillery, 2000: "Economic incentives for rain forest conservation across scales," *Science,* 288: 1828–1832.
92. Schneider, S. H., 1998: "The climate for greenhouse policy in the U.S. and the incorporation of uncertainties into integrated assessments," *Energy and Environment,* 9 (4): 425–440; IPCC, 2001c.
93. IPCC, 2001b, 2001c.
94. Nordhaus, 1994b.
95. Root, T. L. and S. H. Schneider, 1995: "Ecology and climate: research strategies and implications," *Science,* 269: 331–341.
96. Moss and Schneider, 1997, 2000.
97. For example, Titus and Narayanan, 1996; West, J. J., and H. Dowlatabadi, 1999. "Assessing economic impacts of sea level rise," in T. E. Downing, A. A. Olsthoorn,

and R. Tol (eds.), *Climate Change and Risk* (London: Routledge), pp. 205–220; West, J. J., M. J. Small, and H. Dowlatabadi, 2001: "Storms, investor decisions and the economic impacts of sea level rise," *Climatic Change,* 48 (2–3): 317–342; Roughgarden and Schneider, 1999.

98. For example, see the discussion of the hierarchy of integrated assessment models in Schneider, 1997.
99. Schneider et al., 1998.
100. For example, Broecker, W. S., 1997: "Thermohaline circulation, the Achilles heel of our climate system: will man-made CO_2 upset the current balance?" *Science,* 278: 1582–1588; Rahmstorf, S., 1997: "Risk of sea-change in the Atlantic," *Nature,* 388: 825–826.
101. Schneider S. H. and L. H. Goulder, 1997: "Achieving low-cost emissions targets," *Nature,* 389: 13–14.
102. See also Hoffert, M. I., K. Caldeira, A. K. Jain, L. D. D. Harvey, E. F. Haites, S. D. Potter, M. E. Schlesinger, S. H. Schneider, R. G. Watts, T. M. L. Wigley, and D. J. Wuebbles, 1998. "Energy implications of future stabilization of atmospheric CO_2 content," *Nature,* 395: 881–884.
103. For example, Yang, C. and S. H. Schneider, 1998: "Global carbon dioxide emissions scenarios: sensitivity to social and technological factors in three regions," *Mitigation and Adaptation Strategies for Global Change,* 2: 373–404.
104. IPCC, 2000.
105. Keith, D., 2001: "Box 1, Geoengineering," p. 420, accompanying Schneider, S. H., 2001b: "Insight Feature: Earth Systems Engineering and Management," *Nature,* 409: 417–421. See also Chapter 20, this volume.
106. For example, see Moss and Schneider, 1997.
107. For example, see Azar, C., 1996: *Technological Change and the Long-Run Cost of Reducing CO_2 Emissions.* Working Paper, INSEAD, France; Goulder, L. H., S. H. Schneider, 1999: Induced technological change and the attractiveness of CO_2 emissions abatement policies. *Resources and Energy Economics,* 21, 211–253; Grubb, M., M. Ha-Duong, T. Chapuis, 1994: "Optimizing climate change abatement responses: On inertia and induced technology development," in N. Nakicenovic, W. D. Nofdhaus, R. Richels, F. L. Tóth (eds.), *Integrative Assessment of Mitigation, Impacts, and Adaptations to Climate Change* (Laxenburg, Austria: International Institute for Applied Systems Analysis), 513–534; Brugg, M., J. Koehler, and D. Anderson, 1995: *Induced technical change: Evidence and implications for energy-environmental modeling and policy*, Report to the Deputy Secretary-General, OECD; Repetto, R., D. Austin, 1997: *The costs of climate protection: A guide for the perplexed* (Washington, DC: World Resources Institute), 60 pp.
108. Mastrandrea and Schneider, 2001.
109. Schneider, S. H., 2002b: "Modeling climate change impacts and their related uncertainties," in Cooper, R. N. and R. Layard (eds.) *What the Future Holds: Insights from Social Sciences,* (MIT Press, Cambridge, Mass., London), 123–155.
110. Schneider, S. H., K. Kuntz-Duriseti, and C. Azar, 2000: "Costing non-linearities, surprises and irreversible events," *Pacific and Asian Journal of Energy,* 10 (1): 81–106.