What the Future Holds

Insights from Social Science

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Modeling Climate Change Impacts and Their Related Uncertainties

Stephen H. Schneider

Throughout human history, climate has both promoted and constrained human activity. In fact, humans only very recently have been able to reduce their dependence on climate through advances in technology and organization. On the other hand, human actions affect climate. Are our actions causing the climate to change in ways or at rates that will threaten natural systems or make human adaptations difficult? What actions can we or should we take to alleviate the effects of human action on climate change? To approach these questions, we often use mathematical modeling and computer simulations to aid our understanding of the relationship between human action and global climate change. The most comprehensive models of atmospheric conditions are three-dimensional, time-dependent simulators known as general circulation models (GCM). Integrated assessment models (IAM) are important tools to study the impacts of climate change on the environment and society as well as the costs and benefits of various policy options and decisions.

I present a brief overview of the climate debate, modeling, and the current understanding of the climate processes. I discuss how IAMs evaluate the effects of human-induced climate change and the implications of policy options. The critical role of uncertainty is highlighted. Finally, I suggest areas for further consideration.

Can a Forecast Climate Signal Be Detected in the Climate Record?

Twenty thousand years ago, a mere blink in geologic time, a visitor to the now-productive U.S. corn belt would not be sitting in the heart of one of the world's foremost granaries, but rather in open spruce parkland forest, where many of the tree species seen are the same kinds that are found today 500 to 1,000 kilometers north in the boreal forests of Canada (e.g., Wright et al. 1993). Similarly, if we could somehow have been flying over the Great Basin in the U.S. West we would have seen the massive fossil lakes, some stretching hundreds of miles like former Lake Bonneville in Utah, and the now-fossil beaches (currently visible flying into Salt Lake City, Utah Airport, or over Mono Lake, California) from those high water stands that date back 10,000 to 15,000 years ago. The Ice Age, which at its maximum some 20,000 years ago was about 5° to 7 °C colder than our current global climate, disappeared in, what is to nature, a relatively rapid period of about 5,000 to 10,000 years. The average rate of temperature change from the Ice Age to the current 10,000-year period of relative climate stability, our so-called Holocene Interglacial, is about 1 °C change for every thousand years. There were more rapid periods embedded within this time frame (e.g., Broecker 1997), but for the moment, let's only consider the sustained average rates.

Not only did such changes correspond with radical alterations to the ecosystems of the earth, but they have been implicated in the extinction of what is known as the charismatic megafauna (woolly mammoths, saber tooth tigers, etc.). Fossil pollen evidence tells us that the vegetation habitats during the more "rapid" parts of the transition from ice age to interglacial around 10,000 to 12,000 years ago saw what paleoclimatologists call "no analog habitats," that is, combinations of pollen abundances that do not exist on Earth today (Overpeck et al. 1992). All of this change was natural, of course, and there are two reasons for mentioning it in our context of a human perspective. First, to remind us that the climate and ecosystems change by themselves, without influence of humans (the latter is what we call anthropogenic causation), and, two, that climate change of several degrees on a global average basis is a very significant change from the point of view of natural systems.

Explanations of the Ice Age vary, the most popular one being a change in the amount of sunlight coming in between (a) winter and summer and (b) the poles and the equator. These changes in the distribution of seasonal or latitudinal sunshine are due to slow variations in the tilt of the earth's axis and other orbital elements, but these astronomical variations alone cannot totally explain the climatic cycles (e.g., Crowley and North 1991). If these orbital variations and other factors (such as the increased reflectivity of the earth associated with more ice) are combined, our best climate theories (embodied through mathematical models that are composed of the physical laws of conservation of mass, energy, and momentum) suggest that the Ice Age should have been several degrees warmer than it actually was—especially in the Southern Hemisphere. What could account for this extra cold? Perhaps the models are not sensitive enough, that is, they do not respond sufficiently to a change in so-called "radiative climate forcing," which is the change in the amount of radiant energy coming to the earth from external factors like orbital variations or extra ice. Another (more likely, I think) possibility is that something else also changed at the same time.

These theories can be better reconciled with what happened between ice ages (i.e., during interglacials) if one assumes that several watts of energy over every square meter of the earth were taken away in the ice age by some other mechanism at a global scale. But what could be such a mechanism? The obvious candidate would be a change in the composition of the earth's atmosphere, which affects both its reflectivity and its heat-trapping capacity (e.g., decreases in the well-known greenhouse effect or increases in atmospheric dust). But what evidence is there that greenhouse gases, for example carbon dioxide, methane, nitrous oxide, or water vapor, had lower concentrations 20,000 years ago than in the interglacial? In the 1980s that evidence came through loud and clear from the ice caps of the world. Air trapped in these glaciers provides a library of the history of the earth's atmosphere back over 200,000 years. It shows that during the past two ice ages carbon dioxide concentration was about 40 percent less and methane half of the average value during the current and penultimate interglacials (e.g., Eddy and Oeschger 1993). It also shows that since the Industrial Revolution carbon dioxide has increased beyond any levels experienced in the past 250,000 years (at least) by about 30 percent and methane by 150 percent—two figures that virtually no knowledgeable scientist disputes (e.g., IPCC 1996a and 2001a). Moreover, nearly all climate scientists agree that these documented increases in greenhouse gas concentrations are a result of so-called anthropogenic emissions, which are driven by increasing numbers of people pursuing higher standards of living and achieving those growth-oriented goals, through activities such as clearing land, or burning fossil fuels.

If the carbon dioxide and methane decreases in the last ice age help to explain the ice-age coldness, can they tell us something about how the anthropogenic increase of these gases due to human activities might cause climate change in the future? The answer is "not directly," for it is possible that there are other factors we have not accounted for in the ice-age story that could well have been involved, and there are still many unanswered questions associated with the ice-age cycles. It is simply a circumstantial bit of evidence that suggests that the estimated levels of carbon dioxide and methane gases during the ice ages are consistent with the predictions of the greenhouse effect (e.g., Hoffert and Covey 1992). During the ice ages, when surface temperatures were lower by about 5 °C to 7 °C, the estimated levels of greenhouse gases were about half of current levels. From this and other information about ice caps and the distribution of sunlight, we infer that a doubling of CO_2 would raise surface temperatures by about 3 °C plus or minus 1.5 °C. This is known as the "climate sensitivity range." The magnitude of climate sensitivity that best helps to explain the Ice-Age coldness is 2–3 °C. If the best estimate of the temperature change associated with a doubling of CO_2 were ten degrees warming, which is twice the value at the high end of the climate sensitivity range thought by the mainstream climate scientist today (e.g., IPCC 1996a and 2001a), then the ice ages should have been even colder than they were. On the other hand, if the earth would only warm up by half a degree or less if CO_2 doubled, then it would be tougher to explain the magnitude of the ice ages without finding some other mechanism not yet identified. Of course, the latter is possible. So, what other lines of circumstantial evidence or direct evidence do we have for estimating the sensitivity of the climate to greenhouse gas increases?

We know from quite literally thousands of laboratory experiments and direct measurements, millions of balloon observations, and trillions of satellites data bits, that the basic structure of the energy flows in and out of the earth's atmosphere is relatively well understood. We know that water vapor, carbon dioxide, and methane trap enough energy on the earth to warm the surface up about 33 °C relative to that which would occur in their absence.

This well-known natural greenhouse effect is not under dispute and has been known for a century and a half. Nor do most climatologists dispute that there has been about an 0.6 °C (plus or minus 0.2 °C) globally averaged warming trend at the earth's surface over the past century, nor that 1998 was by several tenths of a degree the warmest year globally in the instrumental record (IPCC 2001a). In much greater dispute is whether a small increment in this envelope of greenhouse gases since the Industrial Revolution would produce a noticeable response (i.e., a "climate signal"). It is difficult to detect a small climate signal (less than 0.5 °C) because the natural variability of global surface temperature is several tenths of a degree Celsius from year to year. Also, century-long 0.5 °C global warming trends are not unknown historically, and may have occurred about every thousand years or so. However, as Mann, Bradley, and Hughes (1999) show, the latter half of the twentieth century stands out remarkably as above the climatic noise of the millennium as the warmest period.

The debate over whether that signal has been detected and can be attributed to human activities has been intense. This intensity has been based upon significant recent pieces of evidence (e.g., Santer et al. 1996, Wigley et al. 1998)—albeit each piece is circumstantial—and a few loud, well-publicized denials (e.g., Robinson and Robinson 1997, Singer 1997) that the totality of evidence has any meaning (e.g., see the reviews by Edwards and Schneider 1997, 2001). In the absence of clear, direct empirical evidence, one often has to use either circumstantial evidence or incomplete bits of direct evidence with uncertainties attached—and the nature of those uncertainties explained. When the preponderance of such evidence gets strong enough, then most scientists begin to accept, tentatively of course, the likelihood of causal connections (e.g., chapter 8 of IPCC 1996a). Some people shed their skepticism at different levels than others, so naturally there will be a cacophonous debate over whether a climate signal has been "detected," let alone whether it can be attributed to human activities. One can always find some scientist who will want 999 out of a 1,000 probability of certainty, and others who will accept the proposition at 8 or 9 chances out of 10. And if one adheres to the "precautionary principle," he or she might accept 2 chances out of 10 for a concerning outcome to be concerned. This is not "exact science," but a value judgment about the acceptability and meaning of a significant, but not conclusive, body of evidence. The scientific job is to assess (a) what can happen and (b) what the odds are of its happening (see, for example, this discussion in chapter 6 of Schneider 1997a). Let me discuss this process further.

I have mentioned the ice ages since this is a "natural experiment" that we use, not to forecast a climate map of the future, but to build understanding of climate processes and to validate the tools that we do use to forecast the future (e.g., Schneider 1993)—that is, our climate theories embodied in mathematical models. Are there any other such natural experiments? The answer is "yes, there are several," the two most prominent being (1) episodic volcanic eruptions which throw dust in the stratosphere that reflects for a few years a few watts per square meter of solar energy that otherwise would have reached the lower atmosphere and (2) the seasonal cycle. Let's consider volcanic eruptions first.

Volcanic dust veils should cool the planet. In fact, the effects of the last major eruption, Mt. Pinatubo in 1991, had been independently forecasted by a number of climate modeling groups to cool the earth's lower atmosphere for a few years on the order of several tenths of a degree. Indeed, that is roughly what happened. However, it can be argued that a few tenths of a degree cooling, or warming for that matter, might be a natural internal fluctuation in the earth's climate system, and indeed, as noted earlier, fluctuations of that magnitude are a part of the natural background "climatic noise." How then can we distinguish the climatic signal of the volcanic eruption from the noise of the natural internal variability? In any one eruption it is difficult to do so since the signal to noise ratio is about one, that is, the magnitude of the cooling expected is about equal to the magnitude of the natural internal fluctuations in nonvolcanic years, and therefore for any one volcanic dust event we cannot have very much confidence that a signal has been observed. The fact that the Pinatubo results support the prediction doesn't, by itself, give a lot of confidence, although as a circumstantial bit of evidence it is quite useful. However, another volcanic eruption in 1983, El Chichón, also was followed by several tenths of a degree cooling, as was the effect after the eruptions of Mt. Agung in 1963 or Mt. Krakatoa in 1883.

A number of scientists (e.g., Mass and Schneider 1977) looked at the results from several volcanic eruptions and discovered a clear and obvious correlation between climate and volcanic eruptions. The evidence suggests that a volcanic dust veil in the stratosphere removes a few watts of energy over every square meter of the earth for a few years, and thus, cools the lower atmosphere by a few tenths of degrees—the very magnitude predicted by the same computer models that we use to forecast the effects of a few watts per square meter of sustained (i.e., over a century or more) heating from global greenhouse gas increases.

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What other natural experiments might we have to test climate sensitivity? Another one that happens every year is the change in seasons. Winter predictably follows summer, being some fifteen degrees colder in the Northern Hemisphere and five degrees colder than summer in the Southern Hemisphere. The reason the Southern Hemisphere has a smaller seasonal cycle is because it has much more ocean than land, and water has a higher heat-retaining capacity than land or air. Since a season is not long enough for the planet to reach an equilibrium temperature change, therefore, the more land-dominated Northern Hemisphere has lower heat storage capacity and thus a larger seasonal cycle of surface temperature. How well do the climate models do in reproducing this change? The answer is "extraordinarily well." Although the absolute temperatures that models may simulate can be off by as much as five or six degrees in some regions of the world for some seasons, the models' capacity to reproduce the amplitude of the seasonal cycle of surface air temperatures, by and large, is quite good. (It is less good for some other variables, however, particularly for the hydrological systems—see chapter 5 of IPCC 1996a, and the technical summary of IPCC 2001a.) If we were making a factor of ten error in our estimate of the climate sensitivity, either positive or negative, it would be difficult for the models to reproduce the different seasonal cycle surface temperature amplitudes over land and oceans as well as they do. This is thus another piece of circumstantial evidence suggesting that the current estimate of climate sensitivity is not off by a factor of ten, as some "contrarians" assert. Indeed, indirect evidence like ice ages, volcanic eruptions, and the seasonal cycle simulation skills of models are prime reasons why many of us in the scientific community have for more than twenty-five years expected that clear signs of anthropogenic climate change were not unlikely by the twenty-first century (e.g., see p. 11 of Schneider and Mesirow 1976—in which I projected that "demonstrable climatic changes could occur by the end of this century").

In summary, then, in my opinion it is unlikely that natural variability is the explanation of all recent climate change, especially that which has been documented in the last half of the twentieth century—a point emphasized recently by IPCC (2001a). However, since much of the debate over detection and attribution of human-caused climate change hinges on the projections of climatic models, it is necessary to have at least a cursory understanding of how they work. Although it is impossible to treat more than the highlights of the nature and use of climatic models in only a few pages or so, I nonetheless offer the following section in the hopes of reducing somewhat the confusion that may exist in many peoples' minds after listening to the often acrimonious and technically complex debate over climatic models and their credibility.

Overview of Climate Modeling Fundamentals

Engineers and scientists build models—either mathematical or physical ones—primarily to perform tests that are either too dangerous, too expensive, or perhaps impossible to perform with the real thing. To simulate the climate, a modeler needs to decide which components of the climatic system to consider and which variables to include. For example, if we choose to simulate the long-term sequence of glacials and interglacials (the period between successive ice ages), our model needs to include explicitly the effects of all the important interacting components of the climate system operating over the past million years or so. These include the atmosphere, oceans, sea ice/glaciers (cryosphere), land surface (including biota), land subsurface, and chemical processes (including terrestrial and marine biogeochemical cycles), as well as the external or "boundary forcing" conditions such as input of solar radiant energy (e.g., IPCC 1996a).

The problem for climate scientists is separating out quantitatively cause and effect linkages from among the many factors that interact within the climate system. It is a controversial effort because there are so many subsystems, so many forcings, and so many interacting complex sets of processes operating at the same time that debates about the adequacy of models often erupt. These difficulties are compounded because it is sometimes difficult to determine a trend when there is a large variation around the trend, let alone the possibility that there can be trends in that variability as well.

Modeling the Climate System

So how are climate models constructed? First, scientists look at observations of changes in climate variables, such as temperature, ozone level, and so forth. This allows us to identify correlations among variables. Correlation is not necessarily cause and effect—just because one event tracks another doesn't mean it was caused by it. To assess high confidence to a conclusion, one has to actually prove the relationship is causal and explain how it happened. Especially for cases where unprecedented events are being considered, a first principles or deductive, rather than a purely empirical-statistical, approach is desirable. However, observations can lead to a hypothesis about cause and effect that can be tested. The testing is often based on simulations with mathematical models run on a computer. The models, in turn, need to be tested against a variety of observations, both present and paleoclimatic. That is how the scientific method is typically applied. When a model, or set of linked models, appears plausible, they can be fed unprecedented changes such as projected human "global change forcings" (or pressures placed on the climate system from outside the system, in this case, pressures from human activities) and then be asked to make projections of future climate, ozone levels, forests, species extinction rates, and so forth.

The most comprehensive weather simulation models produce three dimensional details of temperature, winds, humidity, and rainfall all over the globe. A weather map generated by such a computer model—known as a general circulation model or GCM—often looks quite realistic, but it is never faithful in every detail. To make a weather map generated by computer we need to solve six partial differential equations that describe the fluid motions in the atmosphere. It sounds in principle like there's no problem: we know that those equations work in the laboratory; we know that they describe fluid motions and energy and mass relationships (e.g., Washington and Parkinson 1986). So why then aren't the models perfect simulations of the atmospheric behavior?

One answer is that the evolution of weather from some starting weather map (known as the initial condition) cannot be uniquely determined beyond about ten days—even in principle—due to the chaotic internal dynamics of the atmosphere. A weather event on one day cannot be said to determine an event thirty days in the future, all those commercial "long-range" weather forecasts notwithstanding. But the inherent unpredictability of weather details much beyond ten days doesn't preclude in principle accurate forecasts of long-term averages (climate rather than weather). The seasonal cycle is absolute proof of such deterministic predictability, as winter reliably follows summer and the cause and effect is known with certainty. Unfortunately, this distinction between the "in-principle" unpredictability of long-term weather and the possibility of long-term climatic projections is often missed in public debate, especially by nonclimate scientist authors with polit agendas (e.g., Robinson and Robinson 1997).

Grids and Parameterization

The other answer to the imperfection of general circulation model s ulations, even for long-term averages, is that nobody knows how solve those six complex mathematical equations exactly. It's not like algebraic equation where one can get the exact solution by a serie simple operations. There isn't any known mathematical technique solve such coupled, nonlinear partial differential equations exactly. approximate the solutions by taking the equations, which are conti ous, and breaking them down into discrete chunks, which we call g boxes. A typical GCM grid size for a "low resolution" model is about size of Germany horizontally and that of a "high resolution" GCM about the size of Belgium. In the vertical dimension there are two (lo resolution) up to about twenty (high-resolution) vertical layers that t ically span the lowest 10–40 kilometers of the atmosphere. Some refe the grid box as the smallest "grain size" in the model, like the size of dots in a newspaper photo.

In addition, we have a problem of scale: how can we treat proce that occur in nature at a smaller scale than we can resolve by our proximation technique of using large grid boxes? For example, clo are very important to the energy balance of the Earth-atmosphere tem, since they reflect sunlight away and trap infrared heat. Unfor nately, none of us have ever seen a single cloud the size of Belgium, alone Germany; thus, we encounter the scale problem. We cannot culate clouds explicitly because individual clouds are typically the size a dot in this grid box—that is, they are much smaller than the grain of our model. We can put forward a few reasonable propositions cloud physics: if it's a humid day, for example, it's more likely to cloudy; if the air is rising, it's also more likely to be cloudy.

GCMs can explicitly predict the average humidity in the grid b and also whether the air is rising or sinking on average. Using this, can write what we call a parametric representation or "parameter tion" to connect large-scale variables that are resolved by the grid (such as humidity) to unresolved small-scale processes (individual clou Through this parameterization, we can predict grid box-averaged clo iness. So-called "cumulus parameterization" is one of the important—and controversial—elements of GCMs that occupies a great deal of effort in the climate modeling community. Although the models are not ignoring cloudiness, neither are they explicitly resolving individual clouds. Instead, modelers try to get the average effect of processes that can't be resolved explicitly at smaller scales than the smallest resolved scale (the grid box) in the GCM (e.g., Trenberth 1992). Developing, testing, and validating many such parameterizations is the most important task of the modelers (e.g., Root and Schneider 1995), since these parameterizations determine critically important issues like climate sensitivity. Recognizing both the strengths and shortcomings of climate model is crucial to appreciating the value and limitations of GCMs in increasing our understanding of climate change and its impacts.

The Greenhouse Effect

If the earth only absorbed radiation from the sun without giving an equal amount of heat back to space by some means, the planet would continue to warm up until the oceans boiled. We know the oceans are not boiling, and surface thermometers plus satellites have shown that the earth's temperature remains roughly constant from year to year (the interannual globally averaged variability of about 0.2 °C or the 0.5 °C warming trend in the twentieth century, notwithstanding). This near constancy, within a few watts per square meter, requires that, in some form, about as much radiant energy leaves the planet each year in some form as comes in. In other words, a near-equilibrium or energy balance has been established. The components of this energy balance are crucial to the climate.

All bodies with temperature give off radiant energy. The earth gives off a total amount of radiant energy equivalent to that of a black body—a fictional structure that represents an ideal radiator—with a temperature of roughly −18 °C (255 °K). The mean global surface air temperature is about 15 °C (288 °K), some 33 °C warmer than the earth's black body temperature. The difference is due to the well-established natural greenhouse effect.

The term greenhouse effect arises from the classic analogy to a greenhouse, in which the glass allows the solar radiation in and traps much of the heat inside. However, the moniker is a bit of a misnomer because the mechanisms are different. In a greenhouse the glass primarily prevents convection currents of air from taking heat away from the interior. Greenhouse glass is not primarily keeping the enclosure warm by its blocking or reradiating infrared radiation; rather, it is constraining the physical transport of heat by air motion.

Although most of the earth's surface and all clouds (except thin, wispy clouds) are reasonably close approximations to a black body, the atmospheric gases are not. When the nearly black-body radiation emitted by the earth's surface travels upward into the atmosphere, it encounters air molecules and aerosol particles. Water vapor, carbon dioxide, methane, nitrous oxide, ozone, and many other trace gases in the earth's gaseous envelope tend to be highly selective—but often highly effective—absorbers of terrestrial infrared radiation. Furthermore, clouds (except for thin cirrus) absorb nearly all the infrared radiation that hits them, and then they reradiate energy almost like a black body at the temperature of the cloud surface, which is colder than the earth's surface most of the time.

The atmosphere is more opaque to terrestrial infrared radiation than it is to incoming solar radiation, simply because the physical properties of atmospheric molecules, clouds, and dust particles, tend on average to be more transparent to solar radiation wavelengths than to terrestrial radiation. These properties create the large surface heating, or greenhouse effect, that occurs when the atmosphere allows a considerable fraction of solar radiation to penetrate to the earth's surface and then traps (more precisely, intercepts and reradiates) most of the upward terrestrial infrared radiation from the surface and lower atmosphere. The downward reradiation further enhances surface warming and is the prime process causing the greenhouse effect.

This is not a speculative theory, but a well-understood and validated phenomenon of nature (e.g., Raval and Ramanathan 1989). The most important greenhouse gas is water vapor, since it absorbs terrestrial radiation over most of the infrared spectrum. Even though humans are not significantly altering directly the average amount of water vapor in the atmosphere, increases in other greenhouse gases, which warm the surface, cause an increase in evaporation, which increases atmospheric water vapor concentrations, leading to an amplifying or "positive" feedback process known as the "water vapor-surface temperature-greenhouse feedback." The latter is believed responsible for the bulk of the climate sensitivity (Ramanathan 1981). Carbon dioxide (CO_2) is another major greenhouse gas. Although it absorbs and re-emits considerably less infrared radiation than water vapor, CO_2 is of intense interest because its concentration is increasing due to human activities—creating what is known as "anthropogenic radiative forcing." Ozone, nitrogen oxides, some hydrocarbons, and even some artificial compounds like chlorofluorocarbons are greenhouse gases that are also increasing due to human activities. The extent to which these gases are important to the climate depends upon their atmospheric concentrations, the rates of change of those concentrations and their effects on depletion of stratospheric ozone. In turn, lower levels of stratospheric ozone can indirectly modify the radiative forcing of the atmosphere below the ozone layer thus offsetting a small fraction of the otherwise expected greenhouse warming signal.

The earth's temperature, then, is primarily determined by the planetary radiation balance, through which the absorbed portion of the incoming solar radiation is nearly exactly balanced over a year's time by the outgoing terrestrial infrared radiation emitted by the climatic system to the earth. As both of these quantities are determined by the properties of the atmosphere and the earth's surface, major climate theories that address changes in those properties have been constructed. Many of these remain plausible hypotheses of climatic change. Certainly, *the natural greenhouse effect is established beyond a reasonable scientific doubt*, and accounts for natural warming that has allowed the coevolution of climate and life to proceed to this point (e.g., see Schneider and Londer 1984). The extent to which human augmentation of the natural greenhouse effect (i.e., global warming) will prove serious is, of course, the current debate—along with discussions over the potentially offsetting cooling effects of "anthropogenic aerosols" (particles created in the atmosphere primarily from emissions of sulfur dioxide, primarily from burning of high sulfur coal and oil—Schneider 1994; IPCC 1996a and 2001a). (More recently there is some concern that soot particles from unfiltered coal burning, biomass fires, or diesel engines might absorb extra sunlight and further warm the climate, but this debate is still marked by great uncertainties (Jacobson, 2001.))

Model Validation

There are many types of parameterizations of processes that occur at a smaller scale than our models can resolve, and scientists debate which type is best. In effect, as discussed earlier, are these parameterizations an accurate representation of the large-scale consequences of processes that occur on smaller scales than we can explicitly treat? These include cloudiness, radiative energy transport, turbulent convection, evapotranspiration, oceanic mixing processes, chemical processes, ecosystem processes, sea ice dynamics, precipitation, mountain effects, and surface winds. In forecasting climatic change, then, validation of the model becomes important. In fact, we cannot easily know in principle whether these parameterizations are "good enough." We have to test them in a laboratory. That's where the study of paleoclimates has proved so valuable (e.g., Hoffert and Covey 1992). We also can test parameterizations by undertaking detailed small-scale field or modeling studies aimed at understanding the high-resolution details of some parameterized process the large-scale model has told us is important. The Second Assessment Report of IPCC (IPCC 1996a) Working Group I, devoting more than one chapter to the issue of validation of climatic models, concluded that:

> the most powerful tools available with which to assess future climate are coupled climate models, which include three-dimensional representations of the atmosphere, ocean, cryosphere and land surface. Coupled climate modeling has developed rapidly since 1990, and current models are now able to simulate many aspects of the observed climate with a useful level of skill. [For example, as noted earlier, good skill is found in simulating the very large annual cycle of surface temperatures in Northern and Southern Hemispheres or the cooling of the lower atmosphere following the injection of massive amounts of dust into the stratosphere after explosive volcanic eruptions.] Coupled model simulations are most accurate at large spatial scales (e.g., hemispheric or continental); at regional scales skill is lower.

One difficulty with coupled models is known as "flux adjustment" —a technique for accounting for local oceanic heat transport processes that are not well simulated in some models. Adding this element of empirical-statistical "tuning" to models that strive to be based as much as possible on first principles has been controversial (see Shackley et al. 1999). However, not all models use flux adjustments, and those that do seem to get very similar global climate sensitivities to those that don't (e.g., see the discussion and references in IPCC 2001a; see also Rahmstorf and Ganopolski 1999). Nearly all models, with or without this technique, produce climate sensitivities within or near to the standard IPCC range of 1.5 to 4.5 °C. Even though they do not seem to have a major impact on globally averaged climate sensitivity, flux adjustments do, however, have a large influence on regional climatic projections.

Improving coupled models is thus a high priority for climate researchers since it is precisely such regional projections that are so critical to the assessment of climatic impacts on environment and society (e.g., IPCC 1996b; 1997, 1998, and 2001b).

Transient versus Equilibrium Simulations

One final issue needs to be addressed in the context of coupled climate simulations. Until the past few years, climate modeling groups did not have access to sufficient computing power to routinely calculate time-evolving runs of climatic change given several alternative future histories of greenhouse gases and aerosol concentrations. That is, they did not perform so-called transient climate change scenarios. (Of course, the real earth is undergoing a transient experiment—e.g., Schneider 1994.) Rather, the models typically were asked to estimate how the earth's climate would eventually be altered (i.e., in equilibrium) after CO_2 was artificially doubled and held fixed indefinitely rather than increased incrementally over time as it has in reality or in more realistic transient model scenarios. The equilibrium climate sensitivity range has remained fairly constant for over twenty years; assessments by various national and international groups indicate that, were CO_2 to double, climate would eventually warm at the surface somewhere between 1.5 and 4.5°. (Later on we will address the issue of the probability that warming above or below this range might occur, and how probabilities can even be assigned to this sensitivity.)

Transient model simulations exhibit less immediate warming than equilibrium simulations because of the high heat-holding capacity of the thermally massive oceans. However, that unrealized warming eventually expresses itself decades to centuries later. This thermal delay, which retards the climate signal and can lull us into underestimating the long-term amount of climate change, is now being accounted for by coupling models of the atmosphere to models of the oceans, ice, soils, and an interactive biosphere (so-called earth system models—ESMs). Early generations of such transient calculations with ESMs give much better agreement with observed climate changes on Earth than previous calculations in which equilibrium responses to CO_2 doubling were the prime simulations available. When the transient models at the Hadley Center in the United Kingdom and the Max Planck Institute in Hamburg, Germany, were also driven by both greenhouse gases (which heat) and ibly to volcanic dust veils or changes in the earth's orbital elements and the impact of price shocks, or trade policy changes on societal models should bear resemblance to actual societal impacts).

Transients and Surprises

However, a very complicated coupled system like an ESM is likely to have unanticipated results when forced to change very rapidly by external disturbances like CO_2 and aerosols. Indeed, some of the transient models run out for hundreds of years exhibit dramatic change to the basic climate state (e.g., radical change in global ocean currents—e.g., Rahmstorf 1997; Schneider and Thompson, 2000; and Mastrandrea and Schneider 2001). Thompson and Schneider (1982) first investigated the question of whether the time-evolving patterns of climate change might depend on the *rate* at which CO_2 concentrations increased. They used very simplified transient energy balance models to illustrate the importance of rates of forcing on regional climate responses. For slowly increasing CO_2 buildup scenarios, their model predicted the standard outcome: the temperature at the poles warmed more than the tropics.

Any changes in equator-to-pole temperature difference help to create altered regional climates, since temperature differences over space influence large-scale atmospheric wind patterns. However, for very rapid increases in CO_2 concentrations a reversal of the equator-to-pole difference occurred in the Southern Hemisphere. If sustained over time, this would imply difficult-to-forecast transient climatic conditions during the century or so the climate adjusts toward its new equilibrium state. In other words, the harder and faster the enormously complex climate system is forced to change, the higher the likelihood for unanticipated responses. Or, in a phrase, *the faster and harder we push on nature, the greater the chance for surprises*—some of which are likely to be nasty.

Noting this possibility, the Summary for Policy Makers of IPCC Working Group I concluded with the following paragraph (IPCC 1996a, 7):

> Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises." In particular these arise from the nonlinear nature of the climate system. When rapidly forced, nonlinear systems are especially subject to unexpected behavior. Progress can be made by investigating nonlinear processes and subcomponents of the climatic system. Examples of such nonlinear behavior include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

Of course, if the climate system were somehow less "rapidly forced" by virtue of policies designed to slow down the rate at which human activities modify the land surfaces and atmospheric composition, this would lower the likelihood of nonlinear surprises. Whether the risks of such surprises justify investments in abatement activities is the question that integrated assessment (IA) activities (see next section) are designed to inform (IPCC 1996c and 2001c). The likelihood of various climatic changes, along with estimates of the probabilities of such potential changes, are the kinds of information IA modelers need from climate scientists in order to perform IA simulations (Schneider 1997b and 2001). I turn next, therefore, to a discussion of methods to evaluate the subjective probability distributions of scientists on one important climate change issue, the climate sensitivity.

Subjective Probability Estimation

What does define a scientific consensus? Morgan and Keith (1995) and Nordhaus (1994a) are two attempts by nonclimate scientists, who are interested in the policy implications of climate science, to tap the knowledgeable opinions of what they believe to be representative groups of scientists from physical, biological, and social sciences on two separate questions: first, the climate science itself, and, second, policy-relevant impact assessment. The Morgan and Keith surveys show that although there is a wide divergence of opinion, nearly all scientists (e.g., table 5.1) assign some probability of negligible outcomes and some probability of very highly serious outcomes, with few exceptions, like Richard Lindzen at MIT (who is scientist number 5 on figure 1 taken from Morgan and Keith).

In the Morgan and Keith study, each of the sixteen scientists listed in table 5.1 participated in two separate several-hour, formal decision-analytic elicitations of their subjective probability estimates for a number of factors. Figure 5.1 shows the elicitation results for the important climate sensitivity factor. Note that fifteen out of sixteen scientists surveyed (including several 1995 [and 2000] IPCC Working Group I Lead Authors—I am scientist 9) assigned something like a 10 percent subjective likelihood of small (less than 1 °C) surface warming from doubling of CO_2. These scientists also typically assigned a 10 percent or so probability for extremely large climatic changes—greater than 5 °C, roughly equivalent to the temperature difference experienced between a glacial

Table 5.1
Experts interviewed in the study. Expert numbers used in reporting results are randomized. They do not correspond with either alphabetical order or the order in which the interviews were performed. From Morgan and Keith (1995).

James Anderson, Harvard University	Michael MacCracken, U.S. Global Change Research Program
Robert Cess, State University of New York at Stony Brook	Ronald Prinn, Massachusetts Institute of Technology
Robert Dickinson, University of Arizona	Stephen Schneider, Stanford University
Lawrence Gates, Lawrence Livermore National Laboratories	Peter Stone, Massachusetts Institute of Technology
William Holland, National Center for Atmospheric Research	Starley Thompson, National Center for Atmospheric Research
Thomas Karl, National Climatic Data Center	Warren Washington, National Center for Atmospheric Research
Richard Lindzen, Massachusetts Institute of Technology	Tom Wigley, University Center for Atmospheric Research/National Center for Atmospheric Research
Syukuro Manabe, Geophysical Fluid Dynamics Laboratory	Carl Wunsch, Massachusetts Institute of Technology

and interglacial age, but occurring a hundred times more rapidly. In addition to the lower probabilities assigned to the mild and catastrophic outcomes, the bulk of the scientists interviewed (with the noted exception) assigned the bulk of their subjective cumulative probability distributions in the center of the IPCC range for climate sensitivity. What is most striking about the exception, scientist 5, is the lack of variance in his estimates—suggesting a very high confidence level in this scientist's mind that he understands how all the complex interactions within the earth-system described above will work. None of the other scientists displayed that confidence, nor did the Lead Authors of IPCC SAR (or the TAR five years later). In fact, several scientists interviewed by Morgan and Keith expressed concern for "surprise" scenarios. For example, scientists 2 and 4 explicitly display this possibility on figure 5.1, whereas several other scientists—myself among them—implicitly allow for both positive and negative surprises, since they assigned a considerable amount of their cumulative subjective probabilities for climate sensitivity outside of the standard 1.5 to 4.5 range. This concern for surprises is consistent with the concluding paragraph of the IPCC Working Group I Summary

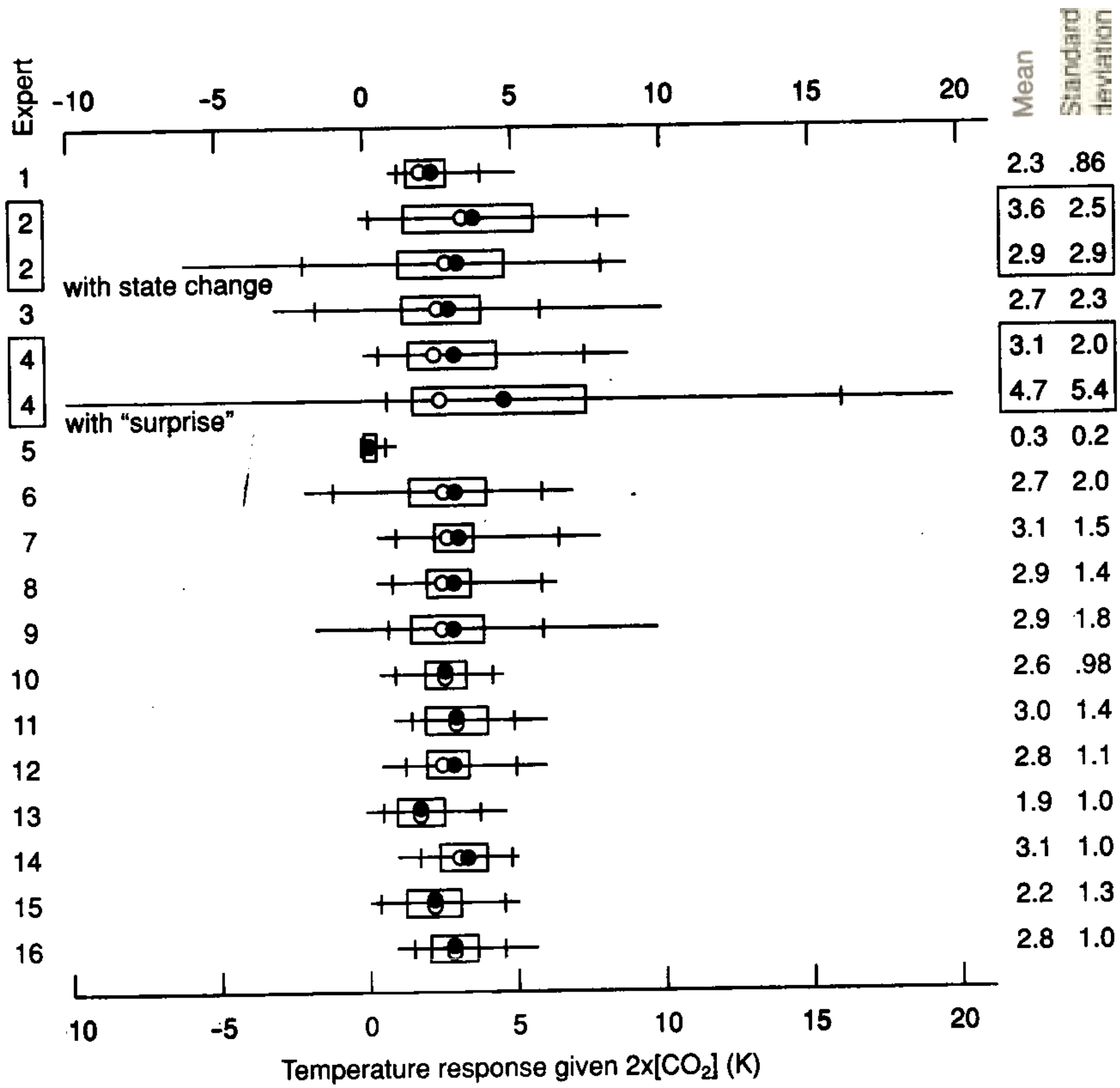

Figure 5.1
Box plots of elicited probability distributions of climate sensitivity, the change in globally averaged surface temperature for a doubling of CO_2 (2x[CO_2] forcing). Horizontal line denotes range from minimum (1 percent) to maximum (99 percent) assessed possible values. Vertical tick marks indicate locations of lower (5) and upper (95) percentiles. Box indicates interval spanned by 50 percent 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 and Keith (1995).

for Policy Makers quoted above and the studies of Rahmstorf (1997), Broecker (1997), and Stocker and Schmittner (1997).

IPCC Lead Authors, who wrote the Working Group I Second Assessment Report, were fully aware of both the wide range of possible outcomes and the broad distributions of attendant subjective probabilities. After several caveats and a number of sentences highlighting such uncertainties, the Report concluded: "Nevertheless, the balance of evidence suggests that there is a discernible human influence on the climate." The reasons for this now-famous subjective judgment were many, such as the kinds of factors listed above. These include a well-validated theoretical case for the natural greenhouse effect, validation tests of both model parameterizations and performance against present and paleoclimatic data, and the growing "fingerprint" evidence that suggests horizontal and vertical patterns of climate change predicted to occur in coupled atmosphere-ocean models have been increasingly evident in observations over that past several decades. Clearly, more research is needed to produce higher confidence, but enough is already known to warrant assessments of the possible impacts of such projected climatic changes and the relative merits of alternative actions to both mitigate emissions and/or make adaptations less costly. That is the ongoing task of integrated assessment analysts, a task that will become increasingly critical in the twenty-first century. To accomplish this task, it is important to recognize what is well established in climate data and modeling and to separate this from aspects that are more speculative. That is precisely what IPCC (1996a) had attempted to accomplish, and IPCC (2001a) carried out to a greater degree. The latter was aided by a lengthy discussion of consistent methods to treat uncertainties, and to use common terms in defining high or low subjective confidence levels. This was facilitated by an IPCC uncertainties "guidance paper," several drafts of which were circulated to IPCC lead authors and revisions made by an iterative process among the lead authors and the guidance paper authors (see Moss and Schneider 2000).

Assessing the Environmental and Societal Impacts of Climatic Change Projections

One of the principal tools used in the assessment of climate change impacts is integrated assessment models (IAMs). These models are often comprised of many submodels adopted and adapted from a wide range of disciplines. In IAMs, modelers "combine scientific and economic aspects of climate change in order to assess policy options for climate change" control (Kelly and Kolstad 1999).

One of the most dramatic of the standard impacts of climatic warming projections is the increase in sea level typically associated with warmer climatic conditions. A U.S. Environmental Protection Agency study (Titus and Narayanan 1996) used an unusual approach: combining climatic models with the subjective opinions of many scientists on the values of uncertain elements in the models to help bracket the uncertainties inherent in this issue. Titus and Narayanan (1996) used formal elicitations on uncertain parameters from teams of experts of all persuasions on the issue and calculated the final product of their impact assessment as a statistical distribution of future sea-level rise, ranging from negligible change as a low-probability outcome, to a meter or more rise, also with a low probability (see figure 5.2). The midpoint of the probability distribution is something like half-meter sea-level rise by the end of the next century.

Since the EPA analysis stopped there, this is by no means a complete assessment. In order to take integrated assessment to its logical conclusion, we need to ask what the economic costs of various control strategies might be and how the costs of abatement compare to the economic or environmental losses (i.e., impacts or damages as they are called) from sea-level rises. That means putting a value—a dollar value typically—on climate change, coastal wetlands, fisheries, environmental refugees, and so forth. Hadi Dowlatabadi, then at Carnegie Mellon University, led a team of integrated assessors who, like Titus, combined a wide range of scenarios of climatic changes and impacts, but, unlike the EPA studies, added a wide range of abatement cost estimates into the mix. Their integrated assessment was presented in statistical form as a probability that investments in CO_2 emissions controls would either cost more than the losses from averted climate change or the reverse (Morgan and Dowlatabadi 1996). Since their results do not include estimates for all conceivable costs (e.g., the human or political consequences of persons displaced from coastal flooding), the Carnegie Mellon group offered its results only as illustrative of the capability of integrated assessment techniques. Its numerical results have meaning only after the range of physical, biological, and social outcomes and their costs and benefits have

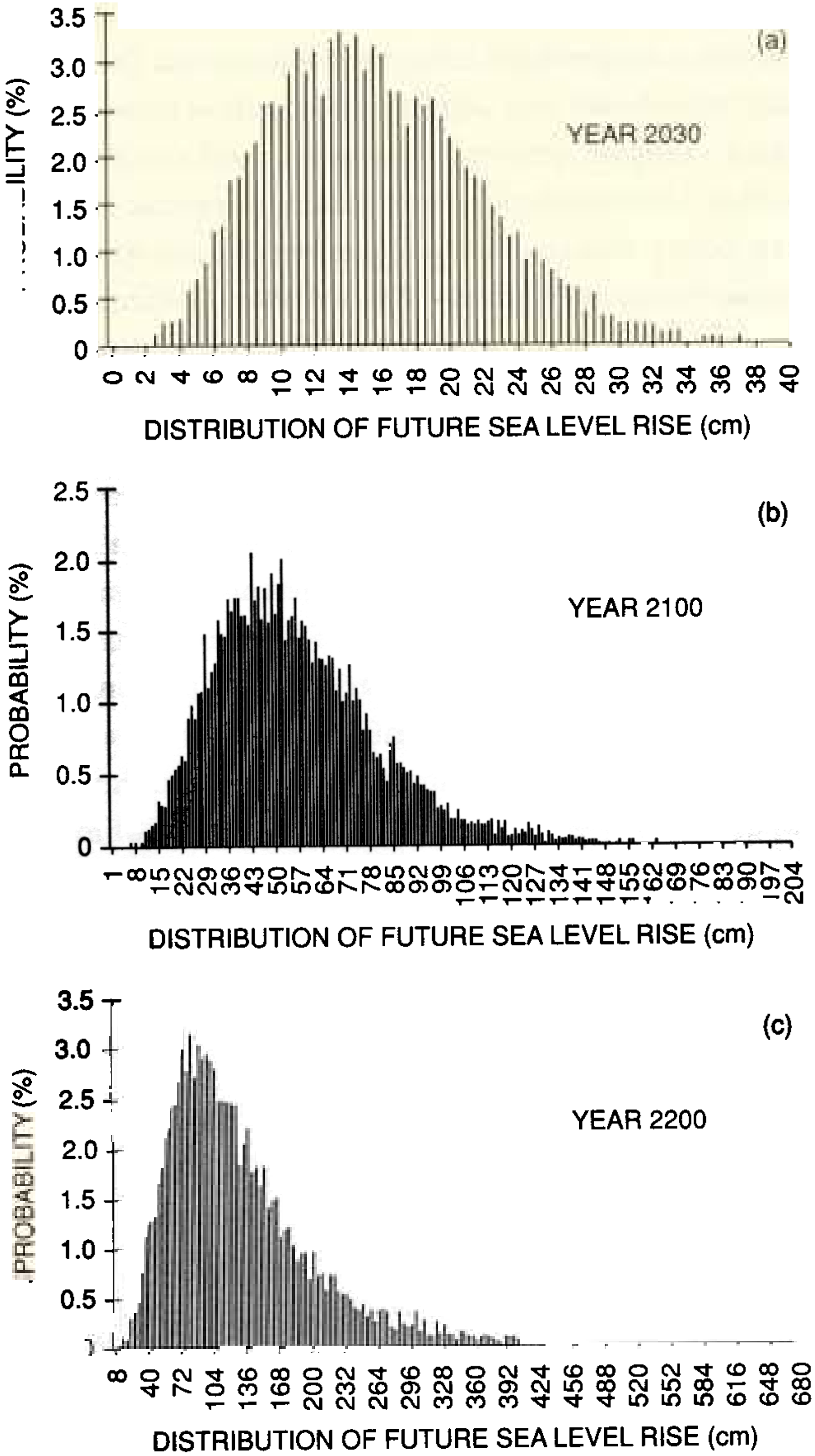

Figure 5.2
Plots showing the probability of various rises of sea level in the years 2030, 2100, and 2200, calculated on the basis of the "Monte Carlo" estimation technique, combining experts' probability distributions for model parameters. From Titus and Narayanan (1994).

been quantified—a Herculean task. Similar studies have been made in Holland by a Dutch effort to produce integrated assessments for policy makers. Jan Rotmans, who heads one of their efforts, likes to point out that such modeling of complex physical, biological, and social factors cannot produce credible "answers" to current policy dilemmas, but can provide "insights" to policy makers that will put decision making on a stronger analytical basis (Rotmans and van Asselt 1996). Understanding the strengths and weaknesses of any complex analytic tool is essential to rational policy making, even if quantifying the costs and benefits of specific activities is controversial (e.g., Schneider 1997b).

William Nordhaus has made heroic steps to put the climatic change policy debate into an optimizing framework. He is an economist at Yale University who has long acknowledged that an efficient economy must internalize externalities (in other words, find the full social costs of our activities, not just the direct cost reflected in conventional "free market" prices to private firms or individuals). He has tried to quantify the external damage from climate change and balance it against the costs to the global economy of policies designed to reduce CO_2 emissions. His "optimized" solution produces a carbon tax, designed to internalize the externality of damage to the climate by increasing the price of fuels in proportion to how much carbon they emit, thereby providing an incentive for society to use less of these fuels—in essence a "polluter pays" principle.

Nordhaus (1992, 1994b) imposed carbon tax scenarios ranging from a few dollars per ton to hundreds of dollars per ton of carbon emitted—the latter would effectively limit coal use in the world economy. He showed that, in the context of his model and its assumptions, these carbon emission fees would cost the world economy anywhere from less than 1 percent annual loss in Gross National Product to a several percent loss by the year 2100. The efficient, optimized solution from classical economic cost-benefit analysis is that carbon taxes should be levied sufficient to reduce the GNP as much as it is worth to avert climate change (e.g., the damage to GNP from climate change). He *assumed* that the impacts of climate change were equivalent to a loss of about 1 percent of GNP. This led to an "optimized" initial carbon tax of about five dollars or so per ton of carbon dioxide emitted rising by several fold to 2100. In the context of his modeling exercise, this would avert only a few tenths of a degree of global warming to the year 2100, a very small fraction of the 4 °C warming his model projected.

How did Nordhaus arrive at climate damage being about 1 percent of GNP? He assumed that agriculture was the most vulnerable economic market sector to climate change. For decades agronomists had calculated potential changes to crop yields from various climate change scenarios, suggesting some regions now too hot would sustain heavy losses from warming whereas others, now too cold, could gain. Noting that the United States lost about one-third of its agricultural economy in the heat waves of 1988, and that agriculture then represented about 3 percent of the U.S. GNP, Nordhaus felt the typically projected climatic changes might thus cost the U.S. economy something like 1 percent annually in the twenty-first century. This figure was severely criticized because it neglected damages from health impacts (e.g., expanded areas of tropical diseases, heat-stress deaths, etc.), losses from coastal flooding or severe storms, security risks from boat people created from coastal disruptions in South Asia or any damages to wildlife (e.g., Sorenson et al. 1998), fisheries, or ecosystems (e.g., IPCC 1996b and 2001b) that would almost surely accompany temperature rises at rates of degrees per century as are typically projected. It also was criticized because his estimate neglected potential increases in crop or forestry yields from the direct effects of increased CO_2 in the air on the photosynthetic response of these marketable plants. Nordhaus responded to his critics by conducting a survey, similar to that undertaken by Morgan and Keith, but this time focused on the impacts of several scenarios of climatic change on world economic product—including both standard market sector categories (e.g., forestry, agriculture, heating and cooling demands) and so-called nonmarket sectors like biological conservation, international equity, and national security. Respondents gave aggregate losses, but also were asked what fraction of those losses were specified in markets (i.e., in Standard National Accounts) and what fraction would be nonmarket. Respondents were not asked to specify which numeraires they used in each case, an issue I'll return to below.

When Nordhaus surveyed the opinions of mainstream economists, environmental economists, and natural scientists (I am respondent number 10 in Nordhaus 1994), he found that the former expressed less anxiety, by a factor of twenty, about the economic or environmental consequences of climate change than the latter (see figure 5.3, in which the bulk of the economists estimates lay toward the left-hand side of the distribution and the natural scientists toward the right). However, even

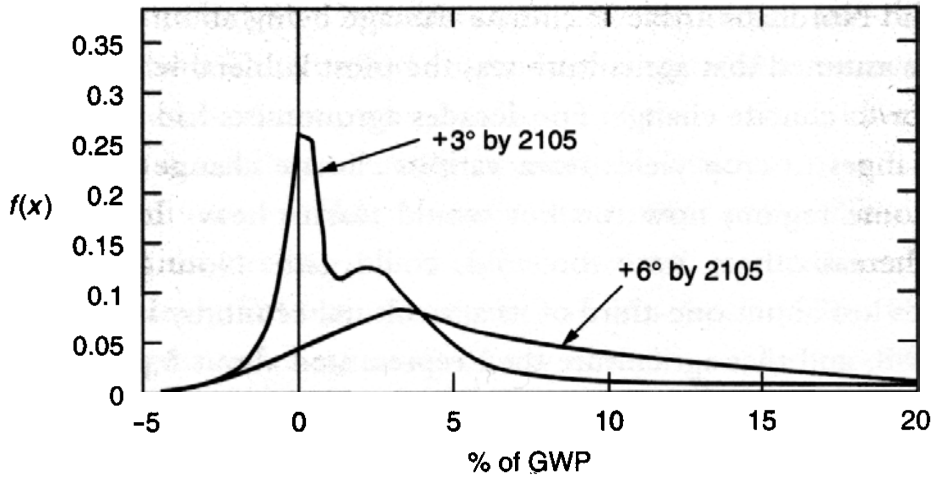

Figure 5.3
Probability distributions $(f(x))$ of climate damages (market and nonmarket components combined) from an expert survey in which respondents were asked to estimate tenth, fiftieth, and ninetieth percentiles for the two climate change scenarios shown. From Roughgarden and Schneider (1999). Data from Nordhaus (1994a).

the conservative estimates of economists Nordhaus surveyed considered there to be at least a 10 percent probability that typically projected climate changes could still cause economic damages worth several percent of gross world product (the U.S. GNP is soon to be around 10 trillion dollars, accounting for about 20 percent of the global total), even when these economists didn't include estimates for possible costs of "nonmarket" damages (e.g., harm to nature or loss of ecosystem services). One ecologist who did explicitly factor in nonmarket values for natural systems went so far as to assign (for 6 °C warming in a century) a 10 percent chance of 100 percent loss of GNP—the virtual end of civilization! While Nordhaus observed that those who know the most about the economy are "comparatively unconcerned," I countered with the obvious observation that those who know the most about nature are comparatively very concerned (e.g., Roughgarden and Schneider 1999, from which figure 5.3 is adapted).

Five Numeraires

One reason for the differences between economists' and natural scientists' relative degrees of concern was the fraction of damages assigned to nonmarket categories. Roughgarden and Schneider (1999) analyzed the Nordhaus (1994a) elicitation data set and found that most respondents who had estimated large damages placed the bulk of them in the nonboth mild and catastrophic eventualities—under their broad umbrella of possibilities. This is a condition ripe for misinterpretation by those who are unfamiliar with the wide range of probabilities most scientists attach to climate change issues (e.g., Ravetz 1986). 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 (see Schneider 1997a, b).

Moreover, these uncertainties "cascade" as wide ranges are given for projections of very different "storylines" for how future societies will be structured (Nakicenovic and Swart, 2000); these storylines condition the range of emissions scenarios, which in turn are expanded by uncertainties in biogeochemical modeling of the dispersion of emissions, compounded further by uncertainties in climatic modeling, climatic impact assessments, and eventually uncertainties in the costs of adaptation and mitigative activities—themselves a function of the very assumptions of how future societies will be structured, since these precondition both adaptive and mitigative capacities (see chapters 2 in both IPCC 2001b and c). This complex interaction where projections of future social conditions govern emissions, which in turn control climatic effects, but in which impacts are not a straightforward response to climatic effects, since adaptations modulate impacts and adaptive capacity, is a function of how future societies are structured—which determined the emissions in the first place. In other words, integrated assessment models need to deal simultaneously with the interconnections among emissions scenarios and adaptive and mitigative capacities of societies over time. This will render single-scenario cost-benefit methods, regardless of how many numeraires are considered, highly tentative, and will be a major challenge to the application of any fixed analytic method to estimating the full range of implications of a variety of social structural assumptions or climate policy proposals (e.g., see chapter 1 of IPCC 2001b). This challenge certainly will keep integrated assessors busy for decades to come.

It is necessary in a highly interdisciplinary enterprise like the integrated assessment of climate change problems that a wide range of possible outcomes be included, along with a representative sample of the subjective probabilities (e.g., Schneider 2001 or Wigley and Raper 2001) that knowledgeable assessment groups like the IPCC believe accompany each of those possible outcomes. In essence, the "bottom line" of estimating climatic impacts at a planetary scale is that both "the end of the world" and "it is good for business" scenarios are the two lowest probability outcomes, and that most knowledgeable scientists and economists consider there to be a significant chance of climatic damage to both natural and social systems. Under these conditions—and the unlikelihood (for reasons given in the above paragraph) that research will soon eliminate the large uncertainties that still persist—it is not surprising that most formal climatic impact assessments have called for cautious, but cost-effective positive steps both to slow down the rate at which humans modify the climatic system and to make natural and social systems more resilient to whatever changes do eventually materialize (e.g., National Academy of Sciences 1991). No such assessments recommend a "wait-and-see" attitude simply because uncertainty is a structural feature of this complex socio-natural system (e.g., Lempert and Schlesinger 2000). It remains to be seen how long it will take for this cautions but positive message to penetrate international climate policy negotiations currently under way.

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