MIT Joint Program on the Science and Policy of Global Change

Uncertainty In Climate Change Policy Analysis

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The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

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SUMMARY

Nations face a long future of discussions and decision-making as they try to manage human impacts on the planet's atmosphere. We are adding steadily to an airborne inventory of gases, including carbon dioxide, methane, nitrous oxide and chlorofluorocarbons, which can influence the radiative balance of the Earth. Because several of these gases have residence times of decades to centuries, any economic and environmental consequences are for practical purposes irreversible on those time scales. On the other hand, the commitment of resources to emissions control also has an irreversible aspect: investment foregone leaves a permanent legacy of reduced human welfare.

Achieving agreement about whether and how to control these emissions would be difficult enough even if the consequences were fully known. Unfortunately, choices must be made in the face of great uncertainty, about both likely climate effects and the costs of control. Of course, if these uncertainties were due to be reduced in a short time, during which the greenhouse gas inventory would grow only a little, then the prudent course would be to wait, so decisions could be made with more complete information. But if the uncertainty is likely to persist for a long time, in terms of the interim greenhouse gas buildup, then decisions to wait bring an ever increasing risk of future damage.

Neither of the extreme positions, to take urgent action now or do nothing awaiting firm evidence, is a constructive response to the climate threat. Responsible treatment of this issue leads to a difficult position somewhere in between. The implications for analysts who would carry out policy assessment are more clear. First, uncertainty is the essence of the issue. Calculations which assume that key uncertain relations can be treated *as if* known with certainty, or which place heavy weight on one or a few simple scenarios, can easily misrepresent both the nature of the problem and the implications of alternative courses of action. A second implication of this survey is that groups analyzing the greenhouse issue must take care not to freeze models of the various processes at current levels of knowledge, or to incorporate simplified representations and carry them forward over time without continuing review and reconsideration of their adequacy.

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UNCERTAINTY IN CLIMATE CHANGE POLICY ANALYSIS

by
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MIT Joint Program on the
Science and Policy of Global Change

1. The Role of Uncertainty in Policy Analysis

Nations face a long future of discussions and decision-making as they try to manage human impacts on the planet's atmosphere. We are adding steadily to an airborne inventory of gases, including carbon dioxide, methane, nitrous oxide and chlorofluorocarbons, which can influence the radiative balance of the Earth. Because several of these gases have residence times of decades to centuries, any economic and environmental consequences are for practical purposes irreversible on those time scales. On the other hand, the commitment of resources to emissions control also has an irreversible aspect: investment foregone leaves a permanent legacy of reduced human welfare.

Achieving agreement about whether and how to control these emissions would be difficult enough even if the consequences were fully known. Unfortunately, choices must be made in the face of great uncertainty, about both likely climate effects and the costs of control. Of course, if these uncertainties were due to be reduced in a short time, during which the greenhouse gas inventory would grow only a little, then the prudent course would be to wait, so decisions could be made with more complete information. But if the uncertainty is likely to persist for a long time, in terms of the interim greenhouse gas buildup, then decisions to wait bring an ever-increasing risk of future damage.

In this paper we discuss the various uncertainties in analysis of greenhouse policy, and at the outset we offer a caution for the reader who has not before explored the complexities of this global system and the limits of our knowledge of it. On the one hand is the temptation to say: "If we know so little that we cannot rule out dire consequences, then we should drastically reduce global emissions *now*. The risks are too great to bear." Taking this view avoids the stress of difficult decisions under incomplete information. Unfortunately it is unrealistic: it gives too little attention to the economic costs and political difficulties that will attend any attempt to suddenly and massively limit greenhouse gas emissions.

At the other extreme is a conclusion that, "If the estimated effects are so uncertain, then the phenomenon may not be real. We should not contemplate costly action until we have clearer evidence that something actually is happening." Again the need to puzzle over difficult decisions is relieved. But this view first ignores the fact that uncertain estimates have an upper as well as a lower limit. It is not just that we are uncertain and therefore may have nothing to worry about because the effects may be small: the existence of uncertainty means that the effects could be substantially *worse* than expected. This view also ignores the irreversibility of effects, resulting from the long residence times of key greenhouse gases in the atmosphere.

We do not attempt to resolve the difficult policy choices that lie between these extreme positions, but pursue a more modest goal. Policy analysis and informed discussion must start with an understanding of the key uncertainties that characterize climate and the influence of human interaction. Thus as an aid to policy debate we summarize the various uncertainties that are relevant to policy, including the economics of emissions, the science of climate, and the ecological and social consequences of climate change. We also attempt to convey an idea of when the most important uncertainties might be resolved, and which of them may prove irreducible. The presentation is addressed to a general audience, since progress on these issues requires communication among people with diverse backgrounds.

1.1 What We Wish to Know

The determinants of global climate and their uncertainties have long been a focus of scientific investigation, without any concern about human influences. The imposition of a strong policy interest serves not only to add salience to the analysis of uncertainty but to channel it in particular directions. As a matter of course, scientists analyze and report the uncertainties in key relationships, in order to reveal the state of theoretical knowledge, the adequacy of the data, and the characteristics of the models used. Methods have evolved for performing this task, and their design usually is driven more by the traditions of scientific investigation than by the needs of decision-makers.

When the purpose is policy discussion, analysis is motivated by the significance of uncertainty for some contemplated action. Thus, uncertainty is highlighted to the extent that its resolution would influence the choice of policy, its stringency, or its timing. Or, in some cases the degree and character of the uncertainty itself may be important to policy choice. It may matter, for example, how well the uncertainties are believed to be understood, which leads to concern with the track record of the analysts who prepare the estimates.

Concern about global climate change focuses research and analysis on helping the policy-making process. We need to make informed decisions about what actions, if any, should be taken to either avoid possible human-induced change, or adapt to it, and when to take them. For example,

> What are the consequences if nations decide to do nothing about greenhouse gases? Will anthropogenic emissions change climate in ways that will have significant effects on natural ecosystems, or on national economies?
>
> Will particular policies (carbon taxes, stabilization agreements among groups of nations, etc.) avoid these climate outcomes? Are these measures worth their cost considering the consequences they are expected to avoid?

Answers to such questions rest on a specification of the climate impacts of interest and the policy responses that are contemplated. Further, making the needed connection between actions and consequences requires analysis of a complex chain of processes. The chain runs from the time pattern of emissions and their transformation into atmospheric gas concentrations, to the way the climate system reacts to the resulting change in the net flows of radiant energy. It then turns to the patterns (and costs) of human adaptation to climate change, and to the determination of the impacts on ecosystems and economic welfare. Finally, it returns to assessment of the economic costs to abate greenhouse gas emissions in the first place.

In a hypothetical world of perfect knowledge, or even low uncertainty, satisfying answers (which we denote here by “X”) to the policy-relevant questions above could, for example, look something like the following:

> If no control measures are taken, global greenhouse emissions will increase by X_1% above current levels by 2100. The resulting changes in radiative forcing will cause a rise in global average temperature of X_2 ˚C over this period.
>
> The associated changes in temperature and precipitation in the grain-growing areas of the United States will yield a X_3% loss in the U.S. grain harvest.
>
> Sea level will rise by X_4 cm over the 21st century, accompanied by increased storms, and the U.S. costs of coastal protection and residual storm damage will be \$$X_5$ million per year. Deciduous forests will be under stress, resulting in X_6% decline in species of trees native to North America. The migration patterns and food sources of several species of birds will be shifted, resulting in potential threats to named species.

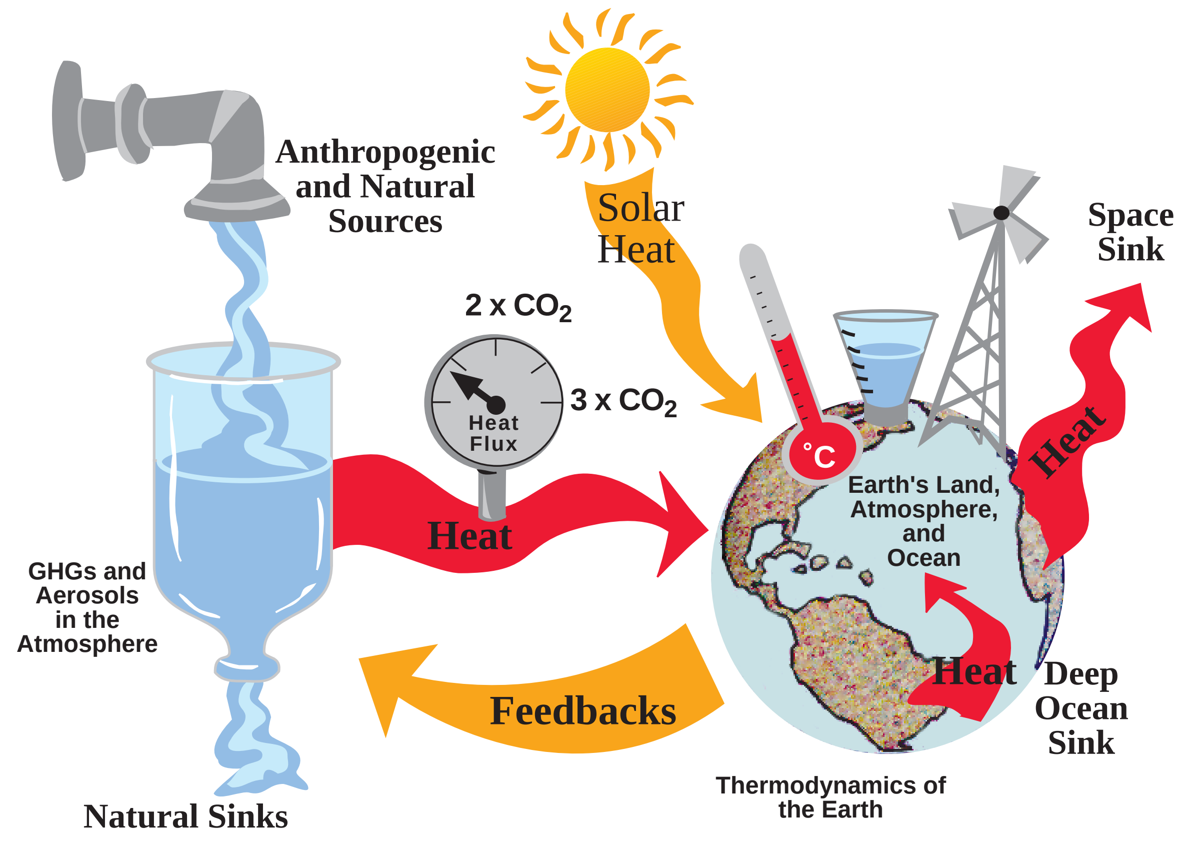

Figure 1. Schematic of the Greenhouse Issue

> An international agreement to reduce developed-country emissions by 20%, and limit those in developing countries to a 50% increase over current levels, will reduce the damages above by X_7%. The cost to the U.S. will be \$$X_8$ billion per year, with the main impact falling on identified industries and states.

Unfortunately for those who must deal with this issue, the present state of understanding and modeling of economic development, climate, and ecology is such that we not only lack precise answers like those represented by X_1 to X_8 above, but for some important phenomena the uncertainty ranges are so wide that the usefulness of the results for policy deliberations is questionable.

1.2 The Climate Process

The system at issue is shown in cartoon-like form in Figure 1. This figure leaves out many important features of climate dynamics but it does provide a useful orientation to a discussion of uncertainty in policy analysis. The climate system is represented as two “source and sink” processes: one for the gases and aerosols (suspended particles, such as in smog) that affect the radiative balance of the globe, and another for the Earth’s balances of heat, moisture, and momentum (involving radiation, winds, and ocean currents).

On the left is a chemical reactor representing the Earth’s atmosphere. Even in its natural state the atmosphere contains all but one set of the greenhouse gases (GHGs) and aerosols of interest, the exception being the chlorofluorocarbons (CFCs). The Earth (biosphere and oceans) inhales and exhales these gases from season to

Climate as we know it, is determined by complex balances involving the fluxes (rates of flow) of energy, momentum, and moisture. The term flux is typically used in climate discussions to refer to the movement of a specified amount of energy (radiation, convective heat), momentum, or moisture through a given area in a given amount of time.

season, and in response to global-scale perturbations (like the El Niño wind and ocean interaction in the equatorial Pacific, and volcanic eruptions), which operate on decadal time scales. With the exception of these decadal phenomena, however, analysis of the record in Greenland and Antarctic ice cores (discussed later) shows that concentrations of GHGs and aerosols have been roughly constant for the last 9,000 years or so. Anthropogenic sources were negligible over almost all of this period, and the natural sources were roughly balanced by the natural sinks.

Then, in the modern period of rapid growth in population and industrial activity, human emissions of GHGs have grown large enough to influence the atmosphere. Net sinks may increase as well, as the biosphere, atmosphere and ocean responds to increased GHG levels, but on the average in recent times the new sources are increasing more rapidly than the sinks, so atmospheric concentrations of GHGs are rising.

The result is the anthropogenic greenhouse effect, illustrated in Figure 1 by an increase in the heat flux from the atmosphere to the Earth. In the present-day context it is an augmentation of a downward flux of radiative heat already occurring as a result of natural greenhouse gases, importantly including water vapor and ozone as well as carbon dioxide, methane, and nitrous oxide. This effect might be measured in tons of coal per year, kilowatts, or any other measure of heat flux, but conventionally it is stated in watts per square meter (W/m^2) of the Earth's surface. This radiant heat flux is referred to as greenhouse "forcing." It should be carefully distinguished from the radiative heat flux from the sun; most of the sun's radiation is visible to the human eye while the atmosphere's emission is in the invisible infrared part of the radiation spectrum. Also, by a calculation described later, the augmented greenhouse effect often is described very approximately in terms of the forcing associated with a specified change in the most important anthropogenic greenhouse gas, CO_2.

The system in Figure 1 operates in the context of an input of solar radiation that is constant for purposes of greenhouse analysis at 340 W/m^2. Over geologic time the solar input has varied, because of small changes in the Earth's orbit and in the total output of the sun. But on time scales of tens to hundreds of thousands of years these variations are extremely small in relation to the changes in radiative forcing associated with human emissions of greenhouse gases (IPCC, 1990). Further, for the past nine millennia, with roughly constant GHGs and aerosols in the atmosphere, the Earth has apparently been in approximate equilibrium with the sun. "Heat in" has roughly equaled "heat out," and the global mean temperature has been near constant, varying up and down from its average value by less than 2 ˚C.

With the additional heat radiated back toward the surface by the atmosphere because of anthropogenic GHGs (counteracted to some degree by anthropogenic or volcanic aerosols which cool by reflecting sunlight back to space) this balance may be disturbed. The additional downward flow of heat has to go somewhere, and on time scales of decades to centuries there are two choices. One direction is ultimately back to space. With the additional heat, the surface of the Earth (land, ice, and the top 100 to 150 meters of the ocean, which is well mixed by winds) warms up, a process indicated by the thermometer in Figure 1, and as the temperature rises the flow of energy from the surface into the atmosphere increases (by radiation and convection). As the atmosphere heats up, the flow of radiant heat back to space will rise until the in-out balance is restored. So, in a crude sense, for any stable level of GHG concentrations there is a corresponding global temperature, so long as the system has reached equilibrium.

This result holds only in some imagined long-run equilibrium, however, which in reality would take millennia to establish. On time

To help understand the heat balance of the Earth, it is useful to imagine that it is like a radiant room heater. Turned on, it draws energy: say, 5 amps at 120 volts, or 600 watts. The element heats up until the rate of flow of outgoing radiant heat (plus some convective heat for this device) rises to 600 watts. At that point the element temperature stops rising, and the heater is in thermodynamic equilibrium with the incoming source (the electricity) and the outgoing sink (the surrounding room).

horizons of decades to several centuries any temperature change will be moderated by the other major current-day sink for heat, the deep ocean. Polar ocean currents carry surface waters to great depths (3 to 5 kilometers) where they may remain circulating slowly and globally for centuries to a millennium before returning again to the surface. Thus, in a time of increasing greenhouse forcing, the surface temperature response is slowed because the ocean (whose capacity for absorbing heat is about 1000 times that of the atmosphere) must be warmed up as well before equilibrium is achieved.

With a rise in temperature, other changes occur as well. At a higher temperature, the atmosphere will hold greater moisture, and a source of water vapor is available from increased evaporation from the oceans. As symbolized by the rain gauge in Figure 1, the water balance of the Earth changes, by means of changes in precipitation, evaporation, transpiration by plants, and runoff. Further, these changes in energy and moisture flows occur in complex patterns, because of the Earth's rotation, the seasons, and the location of land masses. The changes in temperature and water balance create new fluxes of heat and moisture around the surface of globe. These modify the balance of the mass and momentum transfers from one place to another by changes in patterns of winds and ocean currents, indicated in the figure by the windmill.

Looking at the system as a whole, the climate change attributable to human-related GHG or aerosol emissions is conveniently pictured as being determined by these two "source and sink" processes. As discussed below, each is complex in its own right, with many uncertainties. Moreover, to add complexity, a change in climate also changes the rates of climate processes, like the ocean heat sink, and also the sources and sinks of the GHGs and aerosols, both natural and anthropogenic.

Such complexity and uncertainty is not unique to the climate issue, of course: many areas of public policy require decisions under uncertainty about the stakes and the likely effectiveness of alternative policies. But climate change is more challenging than any other current environmental problem. Many of the global-scale physical, chemical and biological processes inherent in Figure 1 are only partially understood. Even if the climate science were well established, forecasting changes on a global scale would be difficult because of insufficient computer power, inadequate observations to define the current state of the system, and the possibility that there may be inherent limits to the predictability of some aspects of climate. In addition, the physics and chemistry of the atmosphere, the chemistry and biology of the land biosphere, and the physics, chemistry and biology of the ocean all interact with one another in ways that are difficult to capture in mathematical models, even with the most advanced computers.

Moreover, climate processes are not the only sources of uncertainty. Social processes that produce greenhouse gases can be predicted over decades or centuries only within very wide bands of uncertainty, and despite recent advances we lack much of the data and analysis needed to illuminate the effects of climate change on natural ecosystems.

It would help, of course, if early stages of any climate change could be observed, and attributed unequivocally to rising greenhouse gas concentrations from present and past human activity. Scientific components of the analysis could thus be verified, and policymakers and the public could calibrate their confidence in predictions of change. Here again, however, the climate system frustrates attempts to understand its behavior. Climate can be usefully thought of as the average weather over several years, and everyone is familiar with the fact that weather is highly variable or “noisy” from day to day, and year to year. The global averages over longer periods (say, decades) are surprisingly variable as well, and evidence of changed global temperature caused by past emissions could easily be drowned in the noise of the system.

There are many complex reasons why the system has such great natural variability, but some are easy to see. Volcanoes throw sulfur gases into the upper atmosphere, and the resulting aerosols (sulfate particles) reflect sunlight and lower global temperature over a period of several years. The oceans, whose influence is indicated in Figure 1, are a dynamic, circulating system, with an ever-changing effect both on the temperature of the atmosphere and even on its chemical composition. If the attempt to observe climate change in data of recent decades is directed at regional instead of global measures, or to possible changes in the frequency of severe storms or droughts, the difficulty of sorting out human-caused greenhouse change is only increased, because on these smaller geographic and time scales the underlying processes are more noisy still.

1.3 A Piecemeal Exploration of Uncertainty

Because the system is so complex, we proceed piecemeal in introducing the system components and their uncertainties, beginning with a common simplification of the issue of climate change and then expanding the canvas to a more realistic picture of the full system. The simplified calculation is the so-called “doubled-CO_2” experiment in which estimates are made of the “equilibrium” climate conditions that particular models yield if given an atmospheric CO_2 concentration twice the present or the pre-industrial (e.g., 1700 AD) level.

Doubled-CO_2 calculations predate both the heightened concern with potential climate change and the growth of understanding of the crucial importance to climate of the deep ocean circulation and the land biosphere. As a result, they do not provide a very realistic picture of climate change in response to human GHG emissions. They emerged as a standard calculation for comparing the behavior of different models of the atmosphere, or for studying alternative formulations of processes within the same model. This was the only calculation that was widely available in the early to mid-1980s. Hence, when climate change emerged as a public issue, the “doubled CO_2” work took on a policy significance beyond its current scientific value, considering our improving knowledge of the system.

Nonetheless, the doubled-CO_2 calculation does provide a convenient context for review of the most important atmospheric processes that determine climate, and the limits to our capacity to forecast them. It also is true that much of the published research on economic and ecological impacts uses climate scenarios based on this calculation. In Section 2 we review these impacts studies and their uncertainties. Along the way, we take the opportunity to illustrate the shortcomings of the doubled-CO_2 results as a guide to policy.

Section 3 turns to the more realistic task of estimating the time path of possible climate change. These so-called “transient” calculations first must take account of the dynamics of the sources and sinks of the gases. The uncertainty in the pattern of human sources derives from the difficulty of forecasting future population and the progress of per-capita growth, and uncertainty about the energy intensity of that growth and associated patterns of land use. Also involved are forecasts of the costs of low-carbon energy supply technologies that may come into use in the next century but are now only dimly perceived. These human emissions are then added to a set of time-dependent natural cycles, most importantly for CO_2 and methane, which lead to ambient GHG and aerosol concentrations. Finally, consideration must be given to the dominant influence of the deep ocean circulation, and uncertainties in its behavior, as it sequesters both heat and CO_2 over time.

Where possible, we try in Sections 2 and 3 to identify the key uncertainties and their magnitudes, and to discuss the likelihood that current research, modeling, and observations will reduce the uncertainties within a period relevant for current policy choices, say ten years.

Section 4 then introduces the most troublesome and poorly understood aspect of forecasts of human influences on climate. There may be irreducible limits to our ability to predict climate, or the effect of GHG emissions, because at some levels of detail the system may be unpredictable due to a phenomenon called "chaos." The characteristics of the system that may lead to this result are summarized, along with aspects of paleoclimate that suggest possible chaotic behavior in the past.

We close, in Section 5, with a brief discussion of the implications of these uncertainties for those who take on the task of informing policymakers and the public about the seriousness of the climate issue and the consequences of the various responses at our disposal.

2. A Focus on the Atmosphere: Climate Sensitivity

2.1 Doubled-CO_2 Calculations

The nature of the doubled-CO_2 calculation is shown in Figure 2, which is a truncated version of Figure 1. A steady level of increased greenhouse forcing, usually expressed as a change in radiative heat flux (in W/m^2), is either computed (from the increase in CO_2 levels) or assumed. The deep ocean, shown in Figure 1, is assumed to be at a temperature in equilibrium with the atmosphere, so there is no ocean heat sink in Figure 2.

The procedure begins with a baseline solution, defined either by current or pre-industrial levels of CO_2 in the atmosphere. Once the model is "tuned" to mimic current climate as closely as possible, it is run again with the same input variables, the one change being a doubling of CO_2 in an early period (an additional greenhouse forcing of about 4 W/m^2 in relation to pre-industrial levels). The model simulation under the new radiative forcing continues until the Earth reaches a new equilibrium, a process usually requiring the calculation of several decades of climate adjustment. The difference in global average or mean temperature between the two runs is then referred to as the "climate sensitivity" as estimated by that particular model.

In fact, the long-lived anthropogenic greenhouse gases are not limited to CO_2, but include methane (CH_4), the chlorofluorocarbons (CFCs), and nitrous oxide (N_2O). In some experiments a mix of these gases may be included, in quantities that yield an "equivalent" CO_2 doubling, but generally the calculation is simplified by assuming that CO_2 is the only long-lived GHG involved. Further, the most important short-lived greenhouse substances are water vapor and clouds, and their levels are determined internally in the climate model. The important intermediate-lived greenhouse gas, ozone (O_3), is usually ignored.

Constructing an analysis in this way is obviously unrealistic, but it conveniently avoids a number of troublesome aspects of the climate system, which we take up in Section 3. The sequestration of heat by the deep circulation of the ocean can be ignored, because the ocean is assumed to be in equilibrium with the atmosphere. Uncertainties about the process of sequestration of CO_2 in the deep ocean and the land biosphere also can be ignored because the

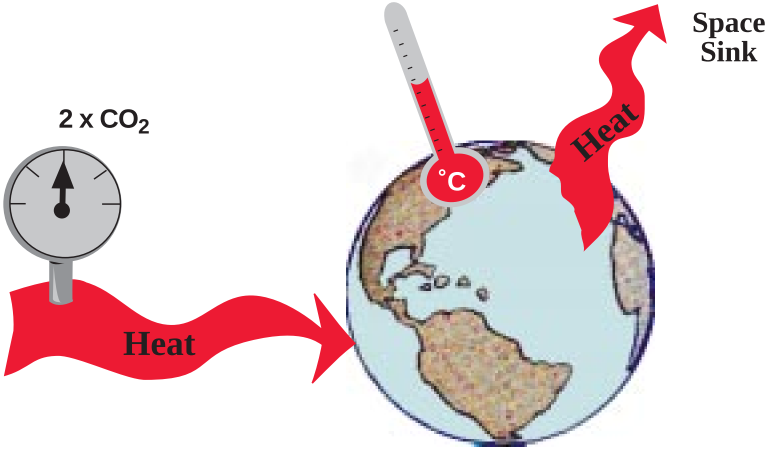

Figure 2. The Doubled CO_2 Experiment

The determination of uncertainty in climate model predictions is difficult due to inadequate information about past climates, which could be used to test the model's predictive capability. Therefore, differences between various models are often used in discussions of uncertainty. We caution, however, that a comparison across models is, at best, a very rough indicator of uncertainty. For example, many of the radiation codes in climate models have a common ancestry, quite apart from the physical laws built in, and little work has been done to prepare and report levels of scientific uncertainty within particular codes. The importance of this caveat is even greater for models of most of the feedbacks.

atmospheric CO_2 concentration is simply doubled, and kept at that level throughout the calculation. Finally, worries that aspects of the climate system may be chaotic (discussed in Section 4) are put aside by formulating the question in terms of a comparison of one equilibrium state (expressed as a statistical mean) to another.

The main indicator of change drawn from this experiment is the difference in global mean temperature, in equilibrium, between the baseline calculation and that with doubled-CO_2, usually stated in ˚C. It is at best a very crude measure of climate response, even for global temperature. It is even weaker for regional temperature, because the distribution over the globe of past changes have varied greatly by latitude and longitude, and current models show different regional average patterns of temperature change (and season-to-season, and day-to-night patterns of change as well) even when the global averages are similar. For precipitation, soil moisture, and other critical variables of interest for estimating impacts of climate change, the geographic variation in model predictions is greater still, as discussed below.

What information does the "climate sensitivity" convey, then? Clearly, it leaves out a great deal of importance; in particular it conveys no information about the pace of any change. Nonetheless it is commonly taken as a preliminary, rough indicator of the "danger" associated with greenhouse gas emissions. If the number is small (say 1 ˚C) and the change is hypothesized to take place over a century or more, its absolute magnitude and pace are within ranges experienced in recent millennia as a result of natural variation, as evidenced by ice-cores and other records. On the other hand, if the calculated sensitivity is significantly higher, say 3 to 4 ˚C, then concern arises about the size and potential rapidity of change, and what the effects might be on ecosystems, and on agriculture and other economic activities. If a change at the upper end of this range is hypothesized to occur within a couple of centuries, the pace is faster than anything experienced in the past 9,000 years (though not faster than documented changes in previous epochs). Also, the temperature would approach levels that ice-core records indicate have not been seen in over 100,000 years, at least in the polar regions where these ice cores are taken.

2.2 Sensitivity With No Feedbacks

As greenhouse gases radiate heat back toward the surface, their net effect can be approximately but conveniently divided into two parts: a "direct radiative effect" leading to small initial changes in temperature, and a number of "feedback processes" that are stimulated by changes in temperature. Just considering the warming that would result from the radiative effect alone, the uncertainty is significant but small in comparison with the uncertainties associated with the feedbacks.

An approximate idea of the uncertainty in this direct effect can be seen in the variation among the results using the radiation computer codes imbedded in the various climate models. They vary over a 34% range in their estimate of the increased radiative forcing of doubled-CO_2 (Cess, et al., 1993) with a central value of the no-feedback equilibrium adjustment of about 1.2 ˚C. The variation comes from several sources. The codes incorporate different simplifications of actual radiative processes, even for CO_2, and explicit consideration of the other greenhouse substances, particularly water vapor and clouds, adds additional complexity which the models cannot handle exactly.

Further research on these processes, and improvements in the models, might lower this uncertainty somewhat. But despite its uncertainty, the direct radiation effect alone is, and will probably remain, a minor component of overall uncertainty about climate sensitivity.

2.3 Feedback Processes in the Atmosphere

The final temperature change including feedbacks is obtained by multiplying the no-feedback estimate by a number called the “gain.” In particular, the above no-feedback estimate of 1.2 ˚C can be amplified (gain exceeds unity) or, less likely, dampened (gain less than unity) by three main physical processes in the atmospheric component of the climate system: planetary reflectivity or albedo feedback, water vapor feedback, and cloud feedback. It is difficult to isolate the effects of these phenomena individually, not just because each is uncertain in its own right, but more importantly because they interact with one another.

When their total effect on the gain is considered, however, the uncertainty in climate sensitivity rises from around 30% for radiation effects alone to a factor of at least three. For example, in recent summaries of the state of climate analysis prepared by the Intergovernmental Panel on Climate Change (IPCC, 1990; IPCC, 1992), a range of 1.5 to 4.5 ˚C is said to summarize current knowledge. Note this range is for uncertainties introduced largely by atmospheric processes, and does not yet properly include the influence of uncertainties in the interaction of the atmosphere with the ocean, covered in Section 2.4.

Note also that a problem arises in interpreting ranges such as those above, which are commonly used to express uncertainty. Usually the range is meant to convey “reasonable” bounds on some quantity. Without additional information about the nature of the uncertainty and the analysis methods used, however, the statement of a range does not tell how likely it is that the “true” value may lie outside its limits. In Section 2.5, we return to these ranges to discuss how they should be interpreted, but first it is useful to review briefly the underlying mechanisms.

In climate science, the “gain” number is a convenient way to express the quantitative effects of the feedbacks. The relation between the feedbacks and the gain is not, however, a simple proportionality. Feedbacks are conveniently quantified by a net feedback number, F, which is the sum of the feedback numbers (positive for positive feedbacks, negative for negative ones) for each of the individual feedbacks. The gain, G, is then the inverse of 1 – F (i.e., G = 1 / (1 – F)). If F is positive, G exceeds unity (amplification), and G becomes infinitely large as F approaches unity. If F is negative, G is less than unity (damping). Current estimates for F vary between 0.2 and 0.8.

2.3.1 Surface Albedo

The albedo or “whiteness” of the planet is the fraction of incident solar radiation that is reflected back to space at the same wavelengths at which it came, and thus is not absorbed by the surface or the greenhouse gases. Albedo is influenced by a number of atmospheric phenomena, such as clouds, aerosols (considered below), and the reflectivity of the Earth’s ice, land, and ocean surface. The primary surface-albedo mechanism affecting climate sensitivity is a change in the area of polar icecaps, glaciers, snow, and sea ice. (Vegetation change, discussed in Section 3, also affects albedo.) With a warmer climate, the Earth may have less snow and ice cover, resulting in a less “white” surface that absorbs more solar radiation, intensifying the warming.

Although the ice-snow feedback is the best understood of these surface albedo processes, there remain important uncertainties. The surface effect is not independent of what may be happening to clouds, and there remain important differences among scientists in the modeling of sea ice. The feedback is generally agreed to be positive, however, thus increasing the gain and magnifying the 1.2 ˚C expected from the direct radiation effect alone. Further, most studies find it to be a smaller feedback than that for water vapor (IPCC, 1992).

2.3.2 Water Vapor

As noted earlier, at higher temperature the lower atmosphere contains more water vapor. Because water vapor is a potent greenhouse gas, it is widely but not universally agreed that this change in concentration is a positive feedback as well. The uncertainty is in its magnitude. The effect of increased water vapor is stronger if it is added in higher latitudes, and at higher altitudes, where radiation plays a larger role in heat transfer relative to convection. The total feedback effect is therefore influenced by atmospheric processes (e.g., large-scale winds, thunderstorms) by which heat and moisture generated in the tropics are redistributed to cooler mid-latitudes and the polar regions, and from the surface to higher altitudes. These processes also are affected by the substantial heat being carried toward the poles by surface currents in the ocean, such as the Gulf Stream. About one-third of the heat transport from equator to pole is carried by ocean currents that warm high-latitude oceans, leading to increased water vapor concentrations in the high-latitude atmosphere.

2.3.3 Clouds

Cloud feedback is the greatest currently known source of uncertainty in the calculation of climate sensitivity. Anyone familiar with the way the temperature is maintained on a cloudy night, but drops on a clear night, or who has experienced the drop in temperature when passing clouds block sunlight in the daytime, is familiar with their radiative properties. The difficulty is that clouds have both these warming and cooling effects, and it is debatable which is the stronger, even for cloud distributions under current climate. Analysis of how the cloud effect will evolve over time is even more complex, involving questions of how cloud dynamics might change with global and regional temperatures, levels of atmospheric moisture, and quantities of atmospheric aerosols.

In the various models used to calculate climate sensitivity, the incremental effect of cloud feedback ranges from strongly positive to slightly negative (IPCC, 1992). When estimated to be strongly positive, the cloud feedback combined with the positive water vapor and ice-snow feedbacks, yields a large positive net feedback and large gain, producing temperature changes near the top of the 1.5 to 4.5 ˚C range commonly cited.

Unfortunately, of the three feedbacks above, the cloud uncertainties are likely to be the most difficult to resolve. The available observations, while including extensive satellite observations, are still inadequate to answer key questions, and the physical processes are not only complex but they occur on a scale (e.g., the size of a thunderstorm or less) which is much smaller than the spatial resolution currently possible in models of global atmospheric circulation. Clearly, cloud dynamics is a high priority for research and analysis to support policy choice, but it is unlikely that the uncertainty in cloud feedback will be completely removed within the next decade.

2.3.4 Coupling the Atmospheric Feedbacks

To consider the effects of these different atmospheric processes on climate system response, a family of computer models has been developed over the past two decades. The ones most commonly used to calculate climate sensitivity are the so-called general circulation models or GCMs, which are three-dimensional (3-D) simulations of the atmosphere. Equations to represent the various processes and their interaction typically are formulated in terms of altitude, latitude and longitude where the effective resolution is 0.1 to 2 km in the vertical and 4 to 10 degrees (200 to 1000 km) in the horizontal, depending on the model. The variety of atmospheric phenomena involved in the above feedbacks are coupled together in these models to determine climate sensitivity.

These models are similar to one another in that they all contain the processes discussed above, along with much additional detail that can be left aside in this discussion of main sources of uncertainty. They differ, however, in the way they represent the key processes, in the methods used to incorporate phenomena that occur at scales less than those resolved in the model, and in mathematical details of their construction and solution. Below we consider uncertainty in the estimates of climate sensitivity drawn from these models, but first we need to show how they can handle the substantial influence of the ocean.

2.4 The Role of the Ocean

To correctly calculate climate sensitivity, the atmosphere modeled above, with its feedbacks, must be linked to a representation of ocean influences. As noted earlier, in doubled-CO_2 experiments the ocean is assumed to be in equilibrium with the atmosphere so that the major role of the ocean in the transition toward equilibrium is conveniently ignored. But this equilibrium assumption applies to annual, global averages of the relevant processes, which still leaves important regional and seasonal effects to be accounted for. In amounts varying by region and season, the atmosphere exchanges heat and moisture with the ocean. It also imparts momentum, as winds help create many of the familiar surface ocean currents. These ocean-atmosphere fluxes help determine the regional distribution of climate and they even influence global averages, like global mean temperature, due to complex interactions among the various climate processes.

The estimation of these fluxes at the atmosphere-ocean boundary and the associated surface currents in the ocean, are yet another source of uncertainty in the results from equilibrium doubled-CO_2 calculations. The nature of the problem can be seen in the baseline solution, which is run with a CO_2 level equal to that in the current atmosphere. Most coupled ocean-atmosphere climate models cannot reproduce current climate conditions. Heat and moisture end up in the wrong location, and analysts override the physics of the models with a set of correction factors, known as flux adjustments. These corrections, computed in the baseline simulation under current forcing, are then kept the same in the simulation with doubled-CO_2.

Most coupled ocean-atmosphere climate models cannot reproduce current climate conditions. Heat and moisture end up in the wrong location, and analysts override the physics of the models with a set of correction factors, known as flux adjustments. These corrections, computed in the baseline simulation under current forcing, are then kept the same in the simulation with doubled-CO_2. A common argument is that the correction appears in both parts of the calculation, with and without increased CO_2, and its influence can be assumed to cancel out when the difference is taken between the two simulations. In fact, however, there is little reason to believe that a correction based on current conditions is appropriate for changed climate, but only recently has any effort been applied to quantification of the uncertainty introduced by our ignorance of this matter. Even more worrisome is the fact that the very need for the flux correction suggests fundamental flaws in the physical understanding and representation of the coupled ocean-atmosphere processes in current climate models.

The seriousness of the problem can be seen in the magnitude of these corrections as reviewed by Gates, et al. (1993). Figure 3 shows data for four current climate models: those of the U.S. Geophysical Fluid Dynamics Laboratory (GFDL), the U.S. National Center for Atmospheric Research (NCAR), the German Max Planck Institute (MPI) and the U.K. Meteorological Office (UKMO). The dotted and dash-dotted lines (identical in each panel) show two independent assessments based on observations of the actual net flux of heat downward at the ocean surface (in W/m^2) plotted by latitude. Clearly shown is the heat flux into the ocean from the warm tropical atmosphere (a positive flux as defined here) and a heat flux from the ocean to the cooler atmosphere at higher latitudes (a negative number).

The solid line in each panel shows these same fluxes as calculated by the particular model. Note the magnitude of the difference between calculated and observed fluxes. For example, at 60˚ North, the GFDL model run reviewed by Gates et al. (1993) departs from the observed data by approximately 50 W/m^2. (To calibrate this discrepancy, recall that the increased radiative forcing associated with a

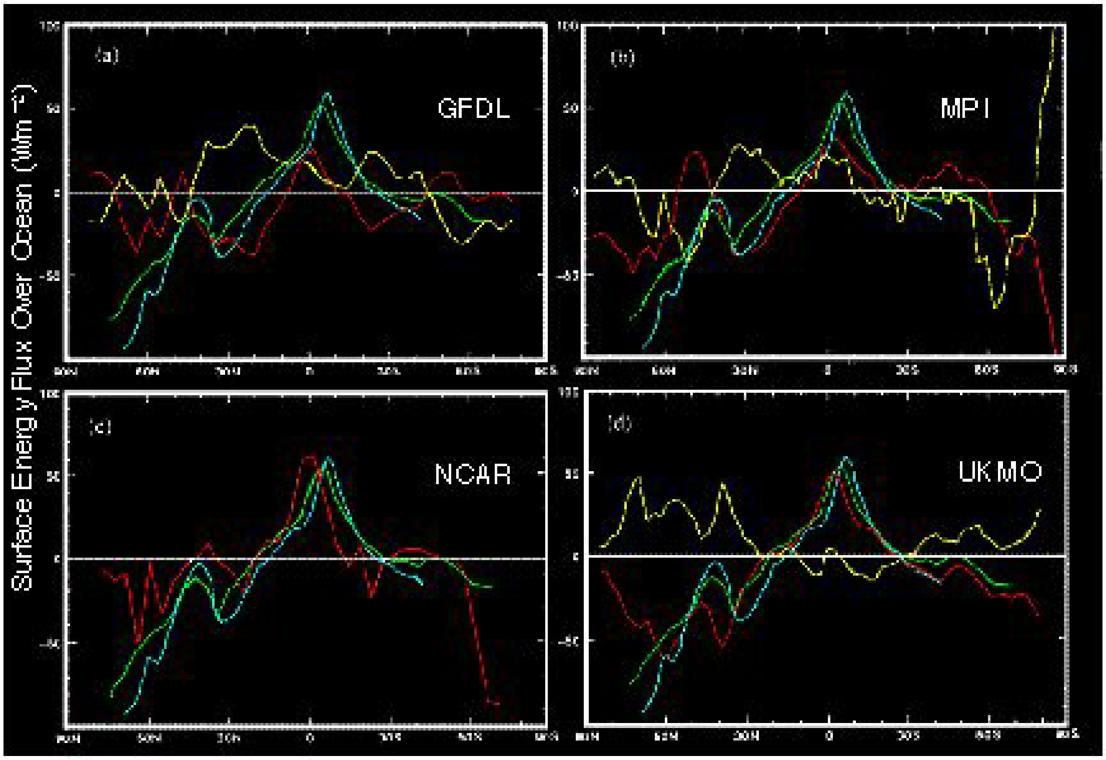

Figure 3. The zonally-averaged annual net downward heat flux at the ocean surface simulated in the control runs of four coupled ocean-atmosphere GCMs (red line), the applied flux correction, if any (yellow line), and the observed flux as estimated by Esbensen and Kushnir (1981) (green line) and by Oberhuber (1988) (blue line). Here the flux correction is to be added to the model simulated flux to obtain the total flux. (From: Gates et al., 1993.)

doubling of CO_2 is in the neighborhood of 4 W/m^2.) Without a correction, the models do not produce current climate patterns when subjected to current radiative forcing levels. In a simulation started with current conditions, even global mean temperature may tend to drift (say by 1 or 2 ˚C) over a period of years (Washington and Meehl, 1989).

In Figure 3, the dashed line shows the flux correction for three of the four models, which is applied to bring the model closer in line with current patterns. Again it can be seen that the numbers are large in relation to possible changes in anthropogenic forcing. Indeed, the numbers shown are longitudinal averages and the corrections at particular locations over the ocean can exceed 100 W/m^2! The NCAR group does not correct its model in this way, but then their calculation of the change associated with CO_2 doubling is taken in relation to a changing base climate that does not approximate the current one.

The flux adjustment procedure is applied in the hope that the correction, which is needed for the model to approximate current climate, will also be appropriate for the simulation under increased forcing and associated changes in climate. A common argument is that the correction appears in both parts of the calculation, with and without increased CO_2, and its influence can be assumed to cancel out when the difference is taken between the two simulations. In fact, however, there is little reason to believe that a correction based on current conditions is appropriate for changed climate, but only recently has any effort been applied to quantification of the uncertainty introduced by our ignorance of this matter (Nakamura et al., 1994). Even more worrisome is the fact that the very need for the flux correction suggests fundamental flaws in the physical understanding and representation of the coupled ocean-atmosphere processes in current climate models.

2.5 The Total Climate Sensitivity

The computer programs for simulating atmospheric processes are large and complex, requiring thousands of input variables. They are expensive and time consuming to solve even if, as with many GCMs used for climate studies, the ocean is represented by a very simple model of the heat and water fluxes. If the atmospheric GCM is coupled to a more complete model of ocean circulation, which attempts to model fluxes at different layers in the ocean and the physical processes that generate them, then the size and complexity are magnified. The overall size is dictated by the numbers and forms of equations needed to model the different processes, and by the "resolution" or level of spatial detail of the component models (e.g., the number of volume elements or grid boxes).

The expense is driven by the size and complexity, and by the fact that the whole model usually must be solved for every 10 to 20 minute step along the way, in order to simulate the atmospheric processes and to avoid numerical problems in the computations. Usually, the smaller the grid box size the more faithfully a model can represent small-scale phenomena in the atmosphere and ocean, and in general the more complete the model of a process the more complicated and numerous the equations. So the demands of these models challenge the limits of each new generation of computers.

Some two dozen of these models have been developed by various groups around the world (IPCC, 1990), and of these roughly a half-dozen are widely viewed, rightly or wrongly, as being the more complete and therefore more credible efforts. Because of differences in structure, assumptions about processes, input variables, etc., they yield different estimates of climate sensitivity. To some degree the differences arise because groups have different views of the fundamental processes (for example, cloud and ocean dynamics). But some of the variation also comes from different accommodations to the computer-derived limitation on grid box size. Many phenomena occur at scales smaller than is feasible to study with these models. Such unresolved phenomena include the process of moist convection by which heat and moisture are transported vertically (e.g., in a thunderstorm), the hydrological processes that determine the moisture in the soil, and many of the dynamical processes in the ocean. Simplified representations (called "parameterizations") must be used to approximate these, and modeling groups differ significantly in their approaches to this task.

Currently, important contributions to the understanding of uncertainty in climate sensitivity come from squeezing information from these modeling efforts, considering their individual pedigrees and the similarities and differences in their results. The natural place to look for help with this task is to the climate modeling community itself, and the most visible example of this approach is the Intergovernmental Panel on Climate Change (IPCC). The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Program, to assess scientific information about climate change and its possible consequences and to formulate response strategies. The first IPCC report concluded that "… the sensitivity of mean global surface temperature to doubling CO_2 is unlikely to lie outside the range 1.5 to 4.5 ˚C", and that, "… a value of 2.5 ˚C is considered to be the best guess" (IPCC, 1990, p. 139). The 1992 update (IPCC, 1992) reconfirmed these estimates.

Three questions arise in interpreting uncertainty in climate sensitivity as summarized by the IPCC and other sources. Where does the range come from? What is meant by the statement that sensitivity is "unlikely" to lie outside the range? And how much attention should be given to that prediction of change that is termed the "best guess"?

The “best guess” by the IPCC for climate sensitivity to doubled CO_2 of 2.5 ˚C lies toward the lower end of their quoted climate sensitivity range (1.5 to 4.5 ˚C). This can be understood by noting that a normal (symmetric) distribution of error in the net feedback number F leads to a skewed distribution in the gain G (see box on page 9).

To illuminate these questions, consider the process that produces “community” estimates of this type. The nature of the model results is illustrated by Figure 4, which constructs a simplified case where three analysis efforts are taken into account. Figure 4a shows the type of results that are in general available. For some models there may be only a single, latest, estimate, as indicated for Models A and C. Other models may have undergone a sequence of recent changes, where improvements were made in the model formulation or its input data, as indicated for Model B. In this process the Model B analysis group will be learning about the behavior of the model, and gaining intuition about the uncertainty in its predictions.

But for none of the extant 3-D GCMs has there been a formal published analysis of the uncertainty in its estimate of some key result, such as climate sensitivity. The result of such an analysis might look something like the distributions for Models X, Y, and Z in Figure 4b, with the details depending on such things as the experimental design underlying the analysis, and the way the effects of various parameterizations are introduced. If this latter type of study were available, then the impression of uncertainty would be less dependent on the differences *among* models, because there would be better understanding of the uncertainty *within* each particular one.

There are several reasons why analysis of the type implied by Figure 4b is not yet available. Funding agencies have not made uncertainty analysis a high priority, and very few climate science groups are focused on the policy issues that make uncertainty so important. More importantly, the analysis is not computationally feasible with current GCM coupled atmosphere-ocean model designs and current computer resources. A calculation of even one equilibrium solution, say with doubled-CO_2, may require simulations requiring many weeks on a supercomputer. But at least 50 or 100 such runs would be required to explore the effect of uncertain input parameters on any one model. (And this assumes the model structure is taken as given; analysis of uncertainty about model structure is an additional large task.) Even with

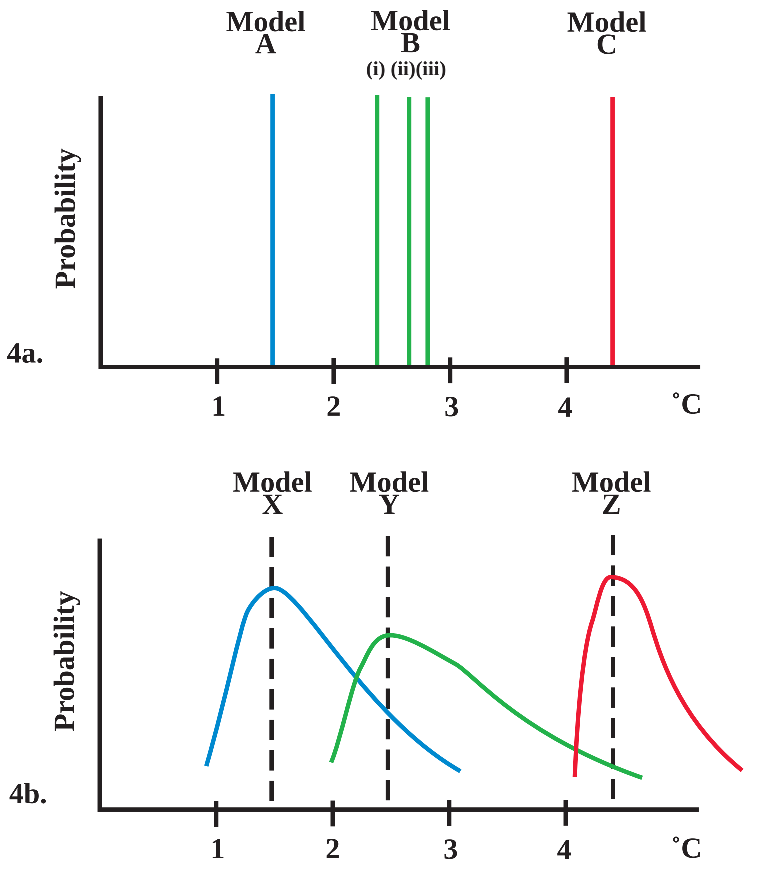

Figure 4. The Nature of GCM Results for 2 x CO_2 Climate Sensitivity

Funding agencies have not made uncertainty analysis a high priority, and very few climate science groups are focused on the policy issues that make uncertainty so important. More importantly, the analysis is not computationally feasible with current GCM coupled atmosphere-ocean model designs and current computer resources. Analysis of the type suggested by Figure 4b is planned at MIT, using a two dimensional (2-D) ocean and land resolving model chosen in large part for its ability to support a large number of runs for uncertainty analysis. But to our knowledge this will be the first effort of this kind, and similar results are not in the offing for the current 3-D versions due to their huge computational demands.

a very efficient experimental design, the required number of runs would far exceed any group's computer resources.

The implication of this concern for the uncertainty within models, and not just among them, is that the range of uncertainty likely is wider than what one would estimate based on the spread of the models themselves. The extent of skewness of the probabilities shown in Figure 4b is also very important since policy discussions can be driven by estimates of the probability for extremes. The scientists, who put together statements like the IPCC quote above, apply their best judgment to select a range based on available models and what they know of the model behavior. But if there is no formal analysis of model uncertainty, their knowledge of the spread is limited and their judgment largely subjective.

In addition, there is here a problem of linguistic imprecision: What is meant by the IPCC statement that the sensitivity is "unlikely" to lie outside the specified range? Is it a 1/100 chance? A 1/5 chance? An individual scientist might impose some explicit subjective probability judgments and compute a more well-specified interval. But as stated by the IPCC, as representing the opinion of a group, it is for policy purposes disturbingly imprecise.

Similar concerns apply to the "best guess" of a 2.5 ˚C temperature increase. In the IPCC (1990) text the authors state that, given the 1.5 to 4.5 ˚C range, "There is no compelling evidence to suggest in what part of this range the correct value is most likely to lie." Frequently in a policy process, however, participants want a single number to simplify deliberations. Or, in the IPCC, such a number was sought for the purpose of illustrating other aspects of IPCC scenarios, like the effects of uncertainty of emissions on future temperature. The problem is that this number is then given a name, "best guess," which conveys an interpretation of certainty (or at least high likelihood) with which some or perhaps most of the participating scientists likely would not agree.

One result of this process of naming, combined with the imprecision of many summary statements about uncertainty, is that these numbers come to have a public interpretation that is only loosely related to the underlying scientific foundation. Based on the weight we observe being given to these figures in policy deliberations to date, it is our impression that this public assessment of current understanding is something like the following. The climate sensitivity to doubled-CO_2 is extremely unlikely (say, less than 1/50) to be less than its no-feedback value (i.e. the gain to be less than unity). The range of 1.5 to 4.5 ˚C is believed to be roughly an 80% confidence interval; that is, there is a only a 15% chance of the "true" sensitivity being below 1.5 ˚C, and a 5% chance of it being above 4.5 ˚C. (Here we attempt to take into account the skewed nature of the IPCC (1992) estimate, as explained in the box on page 14 and illustrated in Figure 4, but just as frequently this skewed nature is ignored in

What is meant by the IPCC statement that the sensitivity is "unlikely" to lie outside the specified range? Is it a 1/100 chance? A 1/5 chance? An individual scientist might impose some explicit subjective probability judgments and compute a more well-specified interval. But as stated by the IPCC, as representing the opinion of a group, it is for policy purposes disturbingly imprecise. There may be good reason for stating the result this way: many participants in the IPCC process may be uncomfortable with the injection of policy-analytic ideas of probability into their scientific work, and the imprecision may be essential if agreement is to be reached on any statement at all.

policy discussions.) Policy discussions treat the results as if the probability distribution of climate sensitivity were significantly peaked at its "best guess" value. Moreover, the level most frequently heard is not 2.5 ˚C, which was the "best guess" value reported in the first IPCC report (IPCC, 1990), but 3.0 ˚C, which has the psychological advantage of being the mid-point of the IPCC (1990) cited range.

Our view of the shortcomings of climate sensitivity as a policy indicator, even if perfectly reported, are emphasized above. However, taking the calculation on face value, our view of the uncertainties is first that the distribution of climate sensitivity is essentially flat over the range cited: there is yet no analytical basis for arguing that any one value or zone in the range is significantly more likely than the others. Further, taking an 80% confidence interval as a standard, we believe the range that deserves to be cited based on current understanding is wider than 1.5 to 4.5 ˚C.

There is hope for clarification of these uncertainties, as the result of efforts at formal analysis now under way at MIT and elsewhere, and in the longer-term uncertainties, which will likely be narrowed as data collection and scientific research proceed. As noted, the key to substantial narrowing of the range of uncertainty in global climate sensitivity appears to be better understanding of convection, cloud formation, and ocean circulation, and progress in these areas with projected resources is expected to be slow over the next decade.

2.6 Climate Details, Regional Effects, and Severe Storms

With these doubled-CO_2 calculations, and the resulting estimates of climate sensitivity, comes a great amount of detail about changes in climate variables other than temperature, and about the regional distribution of changes. When looked at on a regional basis, the differences among the models lead to variations in results that are much greater than that for global mean temperature. Generally, the distribution by latitude of any temperature change is qualitatively similar among models (greater at higher latitudes), but results differ significantly in distributions by longitude. Global precipitation in these models generally rises with global temperature, but the distribution on a regional scale may differ not only in magnitude but in sign.

Changes in temperature and precipitation combine to produce changes in soil moisture, and Figure 5 shows the differences among four GCMs in the predicted equilibrium change from current to doubled-CO_2 for the winter in North America. The blue areas are predicted to be wetter, and the brown ones drier. As can be seen, the four models do not agree for many areas. Of course, these differences among models provide only a very rough suggestion of what might be revealed by a careful analysis of the uncertainty within any particular model.

Regarding extreme events, like drought or severe storms, a number of hypotheses have been put forward, but analysis of such phenomena is in its infancy (Emanuel, 1993; Rodriguez-Iturbe, 1993). Some scientists argue that in a new equilibrium climate, with higher temperatures, moisture levels and, perhaps, momentum, increased numbers of intense storms are likely to result because the total potential energy level of the atmospheric system is higher. And, logically, any region that on average becomes dryer would, in a world of normal weather variability, tend to have more periods that would be classified (based on current patterns) as in drought.

But current GCMs cannot yet simulate very energetic small-scale phenomena like thunderstorms or hurricanes, and they are very limited in their capacity to calculate measures of variability (e.g., droughts and floods) in a future doubled-CO_2 climate. Therefore the range of likely incidence of these events is more uncertain than that for larger aggregates, such as global mean temperature, or even regional temperature and precipitation.

2.7 Economic and Ecological Consequences

The policy concern about climate change is motivated not by meteorological indicators but by what they may imply for human society and

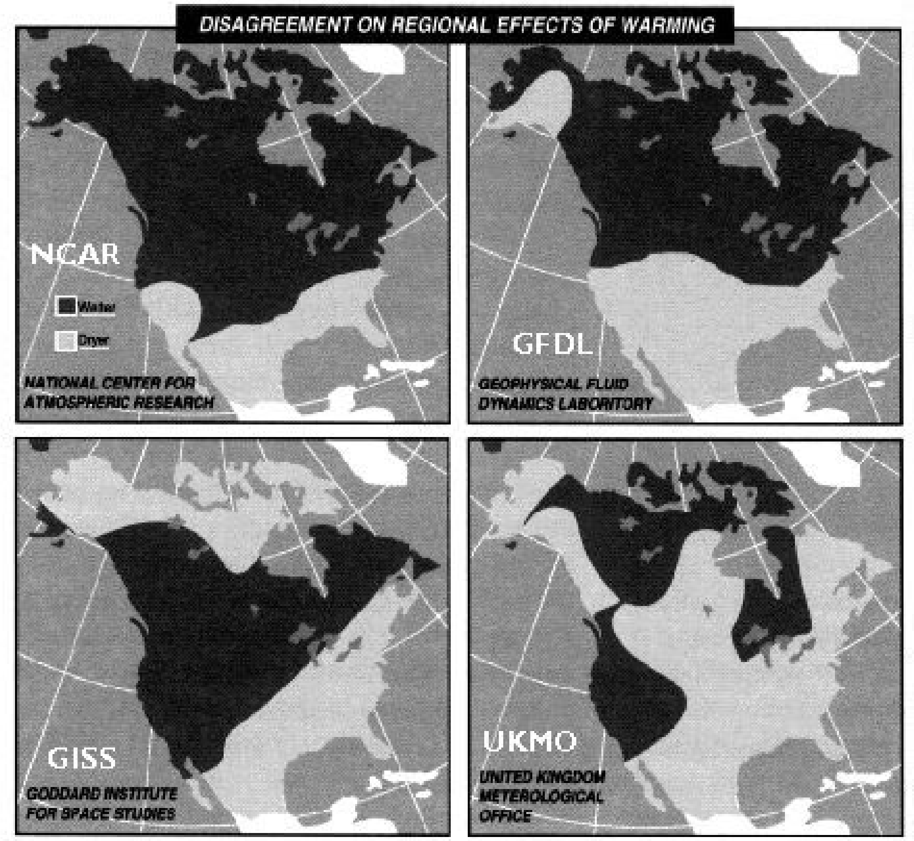

Figure 5. General circulation models contradict one another on how global warming will affect various regions. Even though the four models represented here agree about the effects of a doubling of CO_2 on average global surface temperatures, they disagree on regional changes in soil moisture. (The projections are for winter. Wetter areas are shown in dark grey; drier arieas are shown in light grey.)

natural ecosystems, and analysis of impacts brings its own complications and uncertainties. Because of the diversity and complexity of ecosystems, and of human societies, it is a daunting task even to *catalog* the potential consequences of climate change, much less to quantify each effect individually. Moreover, compared with the research on the physics, dynamics and biogeochemistry involved in climate, the investigation of economic and ecological consequences is in an early stage. Economists and other social scientists have studied the likely impacts (positive and negative) of climate change on social systems, and biologists and ecologists have begun to prepare data on individual ecosystems or particular species (the work is reviewed by Reilly and Thomas, 1993). But the development of aggregate measures of impact is only beginning.

Also, many of the available studies of impacts are based on comparisons between current conditions and a hypothesized future ecological/economic equilibrium with a doubled-CO_2 climate. At the time these impact studies were started, the climate sensitivity calculations discussed earlier were the only ones widely available, and they have had a strong influence here as with a good deal of other policy discussion. Analysis of the far more realistic case of adaptation over time in response to transient climate change is both more difficult and newer, as discussed in Section 3.

The available analysis falls into two rough categories: managed and unmanaged systems. Managed systems include those that can adapt to change in climate under human initiative and control. Among these, the potential impacts seem largest in agriculture, coastal systems subject to sea level and intense storms, water resource systems, and perhaps human health. Many other areas of activity might be effected (Nordhaus, 1991), but they are either relatively small (like effects on water transportation) or well enough understood so they do not add significantly to uncertainty already present in climate itself (e.g., effects on energy supply and demand).

The policy concern about climate change is motivated not by meteorological indicators but by what they may imply for human society and natural ecosystems, and analysis of impacts brings its own complications and uncertainties. Because of the diversity and complexity of ecosystems, and of human societies, it is a daunting task even to *catalog* the potential consequences of climate change, much less to quantify each effect individually. The available analysis falls into two rough categories: managed and unmanaged systems. Managed systems include those that can adapt to change in climate under human initiative and control. Among these, the potential impacts seem largest in agriculture, coastal systems subject to sea level and intense storms, water resource systems, and perhaps human health.

Agriculture is the greatest worry, particularly for less-developed countries, and it has received the most attention from researchers. Several factors complicate the assessment. Farming varies greatly depending on the society, climate zone, and soil condition, so analysis at national or global scale unavoidably suppresses important local detail. For example, a crucial and difficult assumption underlying any assessment is how farmers will adapt to changing climate and associated changes in the prices of their products, and this ability to respond may differ dramatically among different societies.

Most studies of climate effects are based on models of crop growth, and those which take account of adaptation show only small decreases or increases in global agricultural capacity under doubled-CO_2 climate scenarios (e.g., Rosenzweig and Parry, 1993 and 1994; Reilly, Hohmann and Kane, 1994). Available soil moisture is crucial to agriculture, of course, and higher temperatures could have a drying effect. The small predicted effect on agriculture is attributable in part to the fact that forecasts show that in many regions any warming would be accompanied by increased precipitation. (Note that these results are in the context of “equilibrium” adjustment to doubled-CO_2. The conclusions may not hold for a climate in transition.)

Other studies attempt to estimate climate impact by econometric analysis of farm output or land values as a function of climate variables, an approach that will tend to capture more of the potential effects of adaptation. Applied to the United States, this approach shows net losses associated with doubled-CO_2 scenarios of climate change that are smaller than those from the crop model studies (Mendelsohn, et al., 1994).

Furthermore, in agriculture the effect of greenhouse gases is not limited to potential changes in temperature, precipitation and soil moisture: CO_2 has a fertilizing effect on plant growth. Increasing concentrations should increase output, although important details are not yet adequately studied. Evidence is available from greenhouse crops, which often are grown at artificially elevated CO_2 levels, and from controlled experiments. But this experience covers only a few crops, and, even for these, uncertainty remains about how experience under controlled conditions will transfer to the field, where crops confront a host of limiting factors not encountered in the laboratory or greenhouse (Wolfe and Erickson, 1993).

Understanding the uncertainties contributed by all these factors is a daunting task, and no major studies have attempted to do more than cursory assessments of the variability of agricultural output estimates. Also, although global studies show only small change in worldwide total output, some areas benefit and some lose. Thus although the uncertainty may not be of great importance at global scale because the net change is near zero or even positive, it may be extremely important at regional or national scale, where uncertainty is greater and where the stakes may be very high.

A second area of managed systems where large consequences are anticipated is damage to structures from rising sea level. If temperature rises, melting land ice will add water to the ocean, and warming ocean waters will expand in volume. Uncertainty in the effects of thermal expansion is not great for a change to a new temperature equilibrium in the ocean, but the behavior of land ice is poorly understood. Thus for a 3 ˚C rise in global mean temperature the estimates of sea level rise range from 9 to 30 cm (IPCC, 1990). This change might come in combination with an increase in the frequency of severe storms (for reasons cited above), resulting in damage to human settlements and agricultural activities near the coast.

A few studies have been conducted of the costs of flood protection, migration to higher ground, or other forms of adaptation (e.g., Titus, et al., 1991; Wind, 1987), but most are for sites in developed countries. Potential impacts on heavily-populated estuary and delta systems in less-developed countries (like the Nile, the Indus, and the Ganges-Brahmaputra) appear to be large, but the needed detailed analyses remain to be done.

The assessment of water resource systems more generally is in a similar state. Urban water supplies, irrigation networks, flood control, and pollution control systems would all be affected to some degree by the changes in runoff that would accompany shifts in temperature and precipitation (for an overview, see Waggoner, 1990). Some systems would sustain costs of adaptation and residual loss, while others might gain. Unfortunately, only scattered climate effects studies have been carried out in this sector, again mainly in developed countries, so there is little basis for estimating the net impact on a country or large region, even given an accurate climate change prediction. One barrier to reducing the resulting uncertainty is the fact that potential impacts are specific to each river basin, and the needed data gathering and analysis is expensive. Also, here and in the area of coastal damage can be seen another limitation of policy assessment based on timeless or “equilibrium” studies. The costs of adaptation and residual damage depend on the timing of any change and on the degree to which it can be foreseen.

Potential climate effects on human health are a natural concern, but they are even less well understood. Several mechanisms are identified, including changes in nutrition as a side effect of agricultural impacts, increases in heat stress, and changes in the geographical distribution of insect and animal borne diseases (McMichael, 1993). But the magnitudes of potential effects are largely a matter of speculation.

The “unmanaged” components are the natural ecosystems: grasslands, forests, deserts, lakes, and the ocean. They can also adapt to changes in climate, but generally the outcome is not subject to human influence. Here the uncertainty is greatest among the impacts categories, not just due to the complexity of these systems but because so little research has been applied to understanding how they are influenced by climate.

A start has been made on estimating climate influences in terrestrial ecosystems. For example, there are published predictions of the amount of CO_2 fixed by photosynthesis in plants and soils, and released by respiration and decay (Mellilo, et al., 1993) and the resultant net carbon flux (called net primary productivity or NPP) is a rough indicator of ecosystem vitality. Due mainly to fertilization by CO_2, these studies show an increase in NPP on a global basis, under doubled-CO_2 climates from the GCMs discussed above. The global NPP is the sum of often large negative and positive contributions varying according to region. Studies are also being conducted of how the location of different forms of vegetation may shift from the current to a hypothesized doubled-CO_2 condition, and coupled with the climate predictions these studies are being used as preliminary studies of the range of species in an ecosystem and the possible effects of climate change on biodiversity.

Of course, these research efforts are just the first building blocks for constructing an understanding of ecosystem impacts. It is not known to what degree the maintenance of NPP or biodiversity imply survival of all species within an ecosystem, and work is only beginning on the issue of how to combine these diverse effects into a meaningful aggregate measure for a region. The understanding of possible effects on ocean ecosystems, including the all-important fisheries, is poorest of all. It is expected that changes in tidal estuaries and wetlands, resulting from sea-level rise, would affect marine ecosystems. Rising water temperature might have an effect as well. But how these changes interact with the biology of the ocean and its complex

The IPCC (1990, 1992) with few exceptions did not explicitly state the probability of the true value for one of its estimated quantities lying within the quoted error range. This omission is significant since, based on three typical ways of expressing errors in climate science, the probability could be 66% (so-called "one-sigma"), 90%, or 95% ("two-sigma"). These three possibilities correspond respectively to one chance in 3, 10, or 20 of the true value lying outside the quoted range.

chains of organisms, is now on the frontier of research. Substantial reduction of these uncertainties about natural ecosystems is likely a decade or more away, even for a hypothesized doubled-CO_2 climate.

3. EMISSIONS, NATURAL PROCESSES, AND THE DEEP OCEAN: CHANGE OVER TIME

Even with all the effort that goes into the equilibrium calculations of climate sensitivity and associated impacts, as laid out in Section 2, they give at best an approximate picture of the possible effects of greenhouse-related emissions. The impacts of a climate change would be very different depending on whether it occurred over decades or centuries. Also, a change in climate might not be unidirectional: a region destined to become wetter might be drier for a period of perhaps many decades. The actual path for climate change depends on many time-dependent factors, including the progress of economic growth and emissions, the speed of adjustment of natural biogeochemical cycles, and the circulation rates of the surface and deep ocean. Instead of the simplified picture of Figure 2, the analysis must take account of the more complex systems illustrated in Figure 1.

3.1 Sources, Sinks, and Atmospheric Concentrations

Construction of a dynamic picture of climate begins with the sources and sinks for the greenhouse gases because it is the interaction of these two processes that determines atmospheric concentrations in future decades and fixes the time path of radiative forcing. The dynamics of these sources and sinks were not relevant to the above equilibrium doubled-CO_2 calculations, which simply assumed a GHG concentration and thus a radiative forcing level.

3.1.1 Anthropogenic Emissions of Greenhouse Gases

Naturally, the slower the rate of growth in emissions, the longer the time required to build up concentrations in the atmosphere, whatever the behavior of the sinks. Yet even current emissions are subject to uncertainty. For the years 1980-89, the emission of the most important anthropogenic greenhouse gas, CO_2, is estimated by the IPCC (1990) to have been 7.0 GtC/yr (gigatons of carbon per year, where a gigaton is 10^9 tons or 10^{15} gm). The industrial component of emissions can be drawn from fossil fuel consumption data, and the error is low: the estimate is 5.4 ± 0.5 GtC/yr. However, the estimate for net change in land use including deforestation is less sure; it is 1.6 ± 1.0 GtC/yr (that is, the estimate ranges from 0.6 to 3.6 GtC/yr).

Anthropogenic emissions of methane (CH_4) are even less well known. As discussed later, fossil fuel use, rice paddies, cattle and other human activity are estimated to produce 95 ± 25, 85 ± 65, 80 ± 25, and 120 ± 60 $MtCH_4$/yr, respectively (megatons of CH_4 per year where a megaton is 10^6 tons or 10^{12} gm). For nitrous oxide (N_2O) a combination of agricultural, fossil fuel, and chemical industry sources are estimated to produce anthropogenic emissions of 3.5 ± 2.5 MtN/year.

Table 1, taken from the IPCC (1992), shows a set of scenarios of GHG emissions (labeled IS92a through f) that start from current anthropogenic emissions for CO_2 and CFCs and current total emissions for the others. All are supposed to be internally consistent and "possible" in the sense that key assumptions fall within ranges experienced in the past or are consistent with current understanding of the underlying processes. For CO_2 from fossil fuel the estimates span roughly the same range found in other efforts to analyze uncertainty in emissions (Nordhaus and Yohe, 1983; Edmonds, et al., 1984; Margolis, 1992). The estimates vary by a factor of 1.7 by 2025, and by a factor of eight by 2100. For methane, estimated total emissions at the end of the next century vary by a factor of two. The IPCC provides no guidance as to the relative likelihood of outcomes within these ranges, but even if the outliers have low probability the uncertainty remains great.

Emissions predictions are made using models of economic growth and of the associated performance of particular sectors, most importantly energy, agriculture, and forestry. Analysis groups vary in the way they treat regional economies and sectoral detail, but the main uncertainties are driven by a common set of factors (Weyant, 1993). Emissions of CO_2 from fossil fuels are determined by the growth of world economies, the energy intensity of that growth, and how easy it is to substitute carbon-free forms of energy. Emissions of CH_4 and N_2O are influenced by overall growth and energy use, and by the size and intensity of rice and other agriculture and the details of farming practices. We will look at each of these factors and how they contribute to forecast uncertainty. Chlorofluorocarbon (CFC) emissions depend on success in implementation of the Montreal Protocol, and they are presumed to contribute little to overall uncertainty, as suggested by the structure of the IPCC scenarios.

Table 1. IPCC Greenhouse Gas Scenarios

Scenario	Year	CO_2 (GtC/yr)	CH_4 ($MtCH_4$/yr)	N_2O (Mt/yr)	CFCs (Kt/yr)
IS92a	2025	12.2	659	15.8	217
	2100	20.3	917	17.0	3
IS92b	2025	11.8	659	15.7	36
	2100	19.1	917	16.9	0
IS92c	2025	8.8	589	15.0	217
	2100	4.6	546	13.7	3
IS92d	2025	9.3	584	15.1	24
	2100	10.3	567	14.5	0
IS92e	2025	15.1	692	16.3	24
	2100	35.8	1072	18.1	0
IS92f	2025	14.4	697	16.2	217
	2100	26.6	1168	19.0	3

Source: IPCC, 1992.

Population and Economic Growth. In most studies, total economic activity is analyzed as a combined effect of population growth and increase in per-capita production. Thus, one key uncertainty is the growth of population, globally and by region. Population forecasts for a decade or so are not very uncertain: most of the people who will bear children over the period are already alive, and birth and death rates change slowly on this time scale. As a prediction looks farther into the future the uncertainty increases, because these rates can change over several decades, in response to personal and political decisions and changing economic fortunes. A prediction commonly used in GHG modeling is that by the World Bank, which foresees a medium-case world population of 11.3 billion by the end of the 21st century. The estimates used by the IPCC (1992) range from the World Bank's Medium-Low estimate of 6.4 billion to the Medium-High estimate of 17.6 billion.

The World Bank does not indicate how confident it is that population will fall within this range of estimates, but the forecast can be compared with an analysis of past performance of national and international agencies, which showed a standard error of the forecast growth rate of ± 0.3% for developed countries and ± 0.5% for less-developed countries (Stoto, 1984). That is, there is roughly a one in three chance the growth rate actually realized will lie outside a range 0.3% to 0.5% above or below the forecast. With these standard errors, and assuming there is no reason to expect forecasting ability to have improved much over the recent past, the World Bank range used by the IPCC (6.4 to 17.6 billion in 2100) reflects a little less than one standard error for the period to 2025, and substantially less for the period to 2100. In other words, the IPCC range may be optimistically narrow.

Predictions also differ in the methods used to analyze economic growth, including investment in physical and human capital and the resulting increase in economic productivity. They all can be roughly summarized by the rate of per-capita productivity growth that they yield, and this indicator is subject to influences that can be foreseen only dimly many decades into the future. Again a rough impression of the range of uncertainty can be seen in the assumptions that underlie Table 1. Between Scenarios IS92c and IS92e are differences in rates of national per capita growth of 1% per year or more. Over long periods, these small differences grow to have large effects. The difference between 1.5% and 2.5% growth, compounded from 1995 to 2050, yields per capita Gross National Product (GNP) estimates that differ by a factor of 1.7.

One frequently discussed aspect of these estimates is the possibility of positive or negative correlation between the rate of population growth and the rate of growth in per-capita productivity. On the one hand, to sustain very high rates of population increase, resources must be devoted to food shelter and other needs, leaving less for growth-producing investment. On the other hand, population growth provides needed labor for economic expansion. Which condition holds depends on the state of development of the country, among other factors, but the relationship is not well understood, which further contributes to uncertainty about overall growth.

Efficiency Improvement in Energy Use. A forecast of fossil carbon consumption then requires an estimate of the rate of change in energy use per unit of Gross Domestic Product (GDP), apart from those changes attributed to price changes. In several models (e.g., see Burmiaux, et al., 1992) a concept of the Autonomous Rate of Energy Efficiency Improvement, or AEEI, is used. This variable is thought to be in the range of 0.05 to 2.0% per year (Weyant, 1993). Little formal analysis exists to support the choice of level within this range, particularly for many decades into the future, although there is much discussion of currently-available opportunities to reduce CO_2 emissions (NAS, 1992). Compounded over many decades, reasonable differences in the estimated value can grow to be a major component of overall uncertainty in emissions.

Costs of Fossil Energy and Non-Fossil "Backstops." For many decades the discovery of new resources and cost-lowering technical change has overwhelmed the cost-raising depletion of fossil fuel resources. As a result, prices of oil, natural gas and coal, though volatile, have not risen much over the past century. Sooner or later, however, depletion will win out, and prices will begin to rise relative to the prices of other goods and, more importantly, relative to the prices of non-fossil energy. Naturally, the rate of penetration of non-fossil sources will depend on how the prices of the various alternatives evolve over time.

Here, then, are two additional sources of uncertainty that have a substantial effect on emissions forecasts. In the past it has proven difficult to predict resource discovery and technical change in the oil and gas sector, and in the future this should prove no easier. Similar problems arise in predicting the pace of technical change and cost reduction for non-carbon-based energy technologies like solar-based energy (including biomass) and nuclear power, and their environmental acceptability in different societies. Also, there is an issue of foreseeing the pattern of market penetration of these so-called "backstop" non-fossil technologies which, as their economics improve, could replace current technologies.

Agriculture, Forestry, and Land Use. Tropical deforestation is a major source of GHGs, mainly through the release of CO_2 and secondarily through its effects on the budgets of O_3, CH_4, and N_2O. It is a major source of CO_2 emissions uncertainty. Recent estimates place its contribution to the CO_2 source at 1.6 ± 1.0 GtC/yr for the period 1980-89 (IPCC, 1992). This net source is partially or even totally counteracted by the regrowth of forests in the mid-latitudes that were cleared in earlier decades, accelerated perhaps by fertilization by rising CO_2 levels (Table 2). These competing land-use processes are subject to similar degrees of uncertainty in the future, and contribute to the overall uncertainty in CO_2 predictions.

Current uncertainties in CH_4 and N_2O emissions related to agriculture and changes in

Table 2. Annual World Carbon Dioxide Budget, 1980-1989 (GtC/yr)

Industrial Emissions	5.4 ± 0.5
Land Use Change (mainly tropical)	1.6 ± 1.0
Total Emissions	7.0 ± 1.1
Accumulated in Atmosphere	– 3.4 ± 0.2
Sequestered	3.6 ± 1.1
Estimated Ocean Sink	– 2.0 ± 0.8
Inferred Land Sink (extratropical)	1.6 ± 1.4

Based on IPCC (1990, 1992). Errors are assumed normally distributed and are aggregated by summing the squares of the errors, and taking the square-root.

Table 3. Estimated sources and sinks of methane (MtCH_4/yr)

Sources	**Estimate**	**Range**
Natural		
Wetlands	115	100–200
Termites	20	10–50
Ocean	10	5–20
Freshwater	5	1–25
CH_4 Hydrate	5	0–5
Anthropogenic		
Coal mining, Natural Gas and Petroleum Industry	100	70–120
Rice Paddies	60	20–150
Enteric Fermentation	80	65–100
Animal Wastes	25	20–100
Domestic Sewage Treatment	25	?
Landfills	30	20–70
Biomass Burning	40	20–80
Sinks		
Atmospheric Removal (tropospheric + stratospheric)	470	420–520
Removal by Soils	30	15–45
Atmospheric Increases	32	28–37

Source: IPCC (1992).

Table 4. Estimated magnitude of sources and sinks of nitrous oxide (Mt N/yr)

Sources	**Range**
Natural	
Oceans	1.4–2.6
Tropical Soils	3.8–4.8
Wet Forests	2.2–3.7
Dry Savannas	0.5–2.0
Temperate Soils	about 0.6
Forests	0.05–2.0
Grasslands	?
Anthropogenic	
Cultivated Soils	0.03–3.0
Biomass Burning	0.2–1.0
Stationary Combustion	0.1–0.3
Mobile Sources	0.2–0.6
Adipic Acid Production	0.4–0.6
Nitric Acid Production	0.1–0.3
Sinks	
Removal by Soils	?
Photolysis in the Stratosphere	7–13
Atmospheric Increase	3–4.5

Source: Prinn (1994), IPCC (1992).

land use are shown in Tables 3 and 4. As with the effects of deforestation on CO_2 emissions, these uncertainties are even larger when distant future levels are at issue. Methane is produced by the metabolism of microbes, called methanogens, living in oxygen-poor environments. Aside from leakage from the coal and natural gas industries, the main human-caused emissions come from these methanogens, in rice paddies and in the digestive systems of cattle. Rice agriculture and cattle farming will grow with population and economic development, and emissions are subject to the uncertainties of these underlying processes. Also, the emissions per unit of food are not necessarily fixed at today's levels because of possible changes in crop cultivation and animal feeding practices and advances in biotechnology. Nitrous oxide also is produced by soil organisms, but these nitrogen bacteria may either emit or consume N_2O depending on soil conditions, importantly including the moisture level. Estimates of the net N_2O emissions of agricultural soils vary by a factor of 100, as indicated in Table 4.

The Costs of Emission Abatement. The uncertainties in forecasting GHG emissions, irrespective of any specific control policy, all feed directly into the analysis of how costly it might be to reduce emissions or hold them at some specified level (e.g., the commitment by some nations to return emissions to 1990 levels by 2000). The higher the rate of economic growth and the lower the rate of improvement in energy efficiency, the higher the cost of such a

Much of the policy analysis to date assumes policy instruments that economic analysis has shown would achieve control objectives in a least-cost way. Unfortunately for purposes of policy modeling, experience shows that there usually is some distance between these idealized policies and the schemes actually agreed upon by international negotiations or adopted by regional, national and provincial legislatures.

commitment. Also, the economic cost over the long run is sensitive to the costs and rates of penetration of carbon-free energy technologies or low methane producing agricultural options. Like the GCMs discussed above, little effort has gone into the analysis of uncertainty within individual economic models of greenhouse emissions and control cost; most attention has been devoted to comparisons among models (e.g., Weyant, 1993).

Yet another complicating factor in cost analysis is the difficulty of specifying and analyzing realistic versions of the policies that might be adopted to pursue a particular GHG goal. Much of the policy analysis to date (e.g., Burmiaux, et al., 1992; Manne and Richels, 1990; Nordhaus, 1993) assumes policy instruments that economic analysis has shown would achieve control objectives in a least-cost way. These include carbon taxes that are uniform over all fossil sources, schemes of allocation of emission rights with formal systems of trading among nations, or less-formal mechanisms of "joint implementation" wherein nations receive credit for their actions lowering emissions in another nation.

Unfortunately for purposes of policy modeling, experience shows that there usually is some distance between these idealized policies and the schemes actually agreed upon by international negotiations or adopted by regional, national and provincial legislatures. For practical reasons of history, equity, and entanglement with other issues, actual control policies almost never use the most efficient instruments, and so they impose burdens over and above the ideal policy. These effects are easy to foresee beforehand, but hard to specify in detail and to capture in economic models of emissions control cost.

3.1.2 Natural Sources and Sinks for the Gases

The Carbon Cycle. Once emitted, CO_2 is not destroyed appreciably by any process in the atmosphere, but it is converted to other complex organic molecules in photosynthesis-driven biological processes or absorbed mainly as bicarbonate ions (HCO_3^-) in the ocean. Thus CO_2 is said to "cycle" from one medium to another, and human releases in any year are a net addition to large natural movements of CO_2 within the system. In the period 1980-89, the carbon content of the atmosphere is estimated to have risen by a rate of about 3.4 gigatons of carbon per year (GtC/yr), with an estimated error of ± 0.2 GtC/yr (IPCC, 1992). This release must be seen against a background of seasonal CO_2 fluxes of about 60 GtC/yr, primarily a result of leaves growing in the spring and summer (taking up CO_2) and decaying in the fall and winter (releasing it again). Small errors in estimation of the rates of these opposing natural processes can lead to large uncertainties in estimates of future total CO_2 in the atmosphere.

Uncertainties in predicting the carbon cycle are most easily illustrated by looking again at the limits to understanding of current fluxes. Anthropogenic effects in Table 2 (cited earlier) include industrial emissions and the effects of land use change discussed above. Subtraction of the annual accumulation of CO_2 in the atmosphere yields the amount (roughly half) that must be explained by the net effect of some combination of natural sources and sinks.

Current analyses imply that the single largest sink is the ocean. Both chemical and biological complexities are involved in the process by which CO_2 is inhaled and exhaled by the ocean year to year. On the decadal time scales of interest here, however, the bicarbonate in the upper part of the ocean which is mixed by winds and waves (roughly the top 100 to 150 meters) stays in equilibrium with the CO_2 in the atmosphere. That is, as atmospheric CO_2 levels rise, this upper, so-called "mixed layer" absorbs the amount necessary to equalize the CO_2 partial pressures in the air and water. But the capacity of the mixed layer is limited. The massive potential CO_2 sink is the vast volume of water below this level, and so the oceanic uptake of carbon as atmospheric CO_2 rises depends on the action of ocean currents that cause the sinking of surface water to great depth in some areas of the globe. These mass transfers of water are poorly measured and understood at present, which leads to the wide range of uncertainty shown in Table 2 for the ocean sink.

Still, the ocean is not the largest source of uncertainty about the natural sources and sinks. As Table 2 shows, there remains a residual of 1.6 ± 1.4 GtC/yr, which is sometimes referred to as the “missing sink” and must be associated with biological processes on the land, which are not yet well understood. A number of hypotheses about this land sink are under study. One idea involves the fertilization effect discussed earlier, whereby rising CO_2 levels in the air can lead to increased photosynthesis and plant growth and thus to increased carbon storage in living plants and in dead litter in soils. Plant growth also likely is enhanced by the deposition of another nutrient, nitrogen, derived from the nitrogen oxides (NO_x) produced during fossil fuel burning (and also from the use of artificial fertilizers). Finally, some previously cleared land is now in a process of regrowth with net carbon uptake occurring as forests mature. Because plant growth in much of the humid tropics is phosphorus limited, and the land area in the southern hemisphere is too small to explain very much, the search for this “missing sink” is focused on northern hemisphere forests.

When forecasting decades to a century into the future, uncertainty increases, particularly for the poorly-understood land sink. The hypothesized biological processes are themselves influenced by changes in CO_2 and NO_x, and by temperature, rainfall, cloudiness, and soil moisture. Limits to knowledge about current conditions translate into even greater uncertainty about future absorption by both the land and ocean sinks, and thus about the rate of buildup in atmospheric CO_2 concentrations given any pattern of anthropogenic emissions.

The anthropogenic GHGs other than CO_2 (CH_4, N_2O, O_3 in stratosphere and troposphere, and the CFCs) contribute in total roughly half of the additional radiative forcing expected over the next few decades. The radiative effects of all the GHGs are however countered significantly by reduction of sunlight by aerosols. The three main sources of uncertainty are the terrestrial natural and anthropogenic fluxes of CH_4 and N_2O, the radiative effects of sulfate aerosols, and the coupled chemistry of several of the greenhouse-relevant gases.

Cycles of other Gases and Aerosols. The anthropogenic GHGs other than CO_2 (CH_4, N_2O, O_3 in stratosphere and troposphere, and the CFCs) contribute in total roughly half of the additional radiative forcing expected over the next few decades. The radiative effects of all the GHGs are however countered significantly by reduction of sunlight by aerosols. Each individual gas or aerosol contributes its own uncertainty to the overall effect. The three main sources of this uncertainty are the terrestrial natural and anthropogenic fluxes of CH_4 and N_2O, the radiative effects of sulfate aerosols, and the coupled chemistry of several of the greenhouse-relevant gases.

First, the natural fluxes of CH_4 and N_2O are not well understood at the present time. Both gases occur naturally in the atmosphere, and are exhaled (and to a lesser degree inhaled) by the land biosphere in a pattern that is influenced by the seasons and (so it appears) by global-scale events like volcanic eruptions and the El Niño. Methane, as noted earlier, is produced by microbial activity in wetlands, rice paddies and the ocean, and in the stomachs of cattle and termites.

As shown in Table 3, the estimated magnitudes of the natural sources under current climate vary by a factor of roughly two. Anthropogenic sources include the microbe-related processes as well as releases from fossil fuel production and biomass burning, and their estimated magnitude varies by a factor of roughly two as well. (The primary sink for methane involves a set of chemical reactions in the atmosphere, discussed below.) The land sources and sinks of N_2O are even less well known than those for methane. Natural sources include releases by nitrogen bacteria in soils and in the ocean, and, as shown in Table 4, estimates of the magnitudes of natural sources under current climate vary widely (by a factor of two or more) as do the estimates of anthropogenic sources. The sink is better understood: some N_2O may be removed by soils, but the primary mechanism is destruction by ultraviolet (UV) radiation in the stratosphere.

When the focus shifts from quantifying current fluxes to forecasting conditions in the future, the uncertainty again increases. The biogeochemical processes that determine these fluxes all depend on climatic conditions, particularly temperature and soil moisture. If climate begins to change under GHG influence, these processes will change as well, in ways that depend on the regional details of climate. Thus, these dynamic biogeochemical processes are another feedback (shown by the arrow in Figure 1) to be added to the three atmospheric feedbacks discussed in Section 2.

The second major uncertainty involves the atmospheric chemistry that links methane and ozone (O_3). The ozone in the troposphere (roughly, the lower 15 kilometers of the atmosphere) derives from a complex set of chemical reactions involving CH_4, nitrogen oxides (NO_x), carbon monoxide (CO), and the hydroxyl radical (OH). The main sink for CH_4 is reaction with the OH radical, which proceeds fastest in warm air and converts it first to CO and then to CO_2. The OH radical is very reactive and therefore very short-lived (on the order of one second). The rate of loss of methane then depends on both the air temperature and the availability of the OH radical to oxidize it.

The main uncertainties for methane loss therefore concern the production and loss of the OH radical. Its primary source is a reaction involving water vapor, ozone, and UV radiation. Human activity producing NO_x and other gases creates a catalytic cycle in the troposphere, which generates OH by an additional secondary mechanism. But NO_x is short-lived and removed at essentially the same latitude it is emitted. Thus the rate of destruction of methane is influenced by the location of the NO_x emissions as well as by their magnitude, with emissions in the warm tropics having greater influence than in cooler regions. The major sink for OH is reaction with CO and hydrocarbons (including CH_4 itself). Also relevant as OH sinks are the emissions of NO_x and SO_x, which are oxidized by the OH radical to form acid particles. Further, there is an interaction of this system with ozone in the stratosphere, because stratospheric ozone destruction (by chemistry driven by N_2O and CFCs) changes the UV radiation reaching the troposphere, altering OH production and thus the methane loss rate.

The nature of these reactions is now relatively well known, but their net effect, considering the influence of the anthropogenic emissions of several gases and their complex interaction, leads to substantial uncertainty in any forecast of the forcing attributable to human-caused emissions of methane.

Aerosols are the name given to suspended particles (in addition to water and ice) in the atmosphere. Only recently have they become widely appreciated as significant players in climate. Aerosols can cool the Earth by reflecting sunlight back to space or warm the air locally by absorbing radiation. The 1991 eruption of Mt. Pinatubo in the Philippines injected about 20 Mt (megatons or 10^{12} gm) of sulfur dioxide (SO_2) into the stratosphere. The SO_2 cloud spread out, and had a worldwide distribution after about 20-30 days. Over this same time scale the SO_2 is oxidized by OH and combines with water vapor to form sulfuric acid particles. These particles efficiently reflect sunlight back to space. Calculations using climate models, and the observed abundances of the sulfuric acid aerosols, predicted that the Earth should cool for a few years by up to 0.6 ˚C. Indeed, such a global cooling was observed between 1991 and 1993. So there is little doubt that these aerosols are an important influence on the climate, but their influence is sporadic.

Volcanoes are not the only source of

sulfuric acid aerosols. When coal is burned without complete desulfurization, SO_2 is produced and emitted into the lower atmosphere. In the lower atmosphere, the oxidation of the SO_2 again produces sulfuric acid aerosols. These reflect sunlight back to space, as they do in the stratosphere; they can also provide condensation nuclei for clouds. Adding more condensation nuclei to a given volume of water vapor potentially forms more cloud droplets from the same volume of water. That makes the cloud more reflective. The calculated radiative forcing (cooling) by these effects is very substantial, ranging from 1 to 4 W/m^2 over the northern hemisphere mid-latitude land areas.

To assess the significance of these anthropogenic effects, note that a change in radiative forcing of 4 W/m^2 is predicted due to doubling CO_2 levels from present values. But the aerosols cool while the carbon dioxide warms. Note the implied cooling by aerosols in the northern hemisphere significantly offsets implied warming by rising greenhouse gases. While there is still debate over the magnitude of the aerosol effect (e.g., combustion-related pollutants like soot can darken the normally white H_2SO_4 aerosols, thus lowering their reflectivity), there is little doubt that it is a cooling influence that has to be taken into account.

3.2 The Ocean Sink for Heat

As illustrated in Figure 1, the sum of the effects of the various sources and sinks of greenhouse gases is a change over years and decades in the net radiative heat flux to the Earth's surface. Were it not for the influence of the deep ocean, relatively little uncertainty (measured in years not percentages) would attend the timing (if not the magnitude) of the resulting change in global temperature. The land and the wind-mixed layer of the ocean would warm until a new radiative balance was established. The pace of adjustment of land and sea ice (and thus the time pattern of the albedo feedback) is not known precisely, but the error is small compared to that introduced by the deep ocean.

Two of its characteristics make the ocean a particularly troublesome object for study, complicating efforts to reduce uncertainty about its behavior. First, great expense is required to take measurements below the ocean surface, and so observations are sparse for key density-determining variables like temperature and salt content (salinity), by region and depth. And second, because of differences in their density distributions and the forces driving them, important processes take place on smaller geographical scales in the ocean than in the atmosphere. As pointed out earlier, atmospheric scientists achieve important understanding using models with a resolution of 200 or even 1000 km in the horizontal direction. In the ocean, horizontal resolution on the order of 10 km is needed to resolve features like the Gulf Stream. The computational task is vastly increased.

> The eruption of Mt. Pinatubo in 1991 provided a measure of the adjustment rate to changes in radiative forcing on time scales too short to involve the deep ocean. This initial speed of adjustment can be seen specifically in the response rate of global mean temperature to the reflective aerosols derived from this volcano. This temperature decreased by roughly 0.25 ˚C per year for a couple of years, a process that is now reversing almost as rapidly as the aerosol is removed by natural processes. If the aerosols had remained indefinitely, the equilibrium cooling would have been about 5 ˚C and (at a rate of 0.25 ˚C per year) would have been attained in about 20 years if the deep ocean were not involved.

A key place where these limitations matter is precisely in the analysis of deep ocean circulation, which is involved in climate change as a sink of both heat and CO_2. The so-called "thermohaline" circulations that accomplish mass transfers of water (and thus of CO_2, heat and salt) from the mixed layer to deeper levels appear to originate on very small scales, and the resulting deep currents may meander and disperse for tens of thousands of miles before "upwelling" again to the surface. The global patterns of these currents, known popularly as the "conveyor belt," are approximately known, and some insight into volumes and rates of movement can be drawn from the distribution in the ocean of fallout from nuclear bomb testing or human-created chemicals like CFCs. But key quantities are highly uncertain and the likely responses of these currents to temperature changes at the surface are in the early stages of analysis.

As a result of these limits to knowledge, estimates of the timing of the Earth's response to the greenhouse forcing can vary widely. Take, for example, the hypothesis of a doubling of CO_2 occurring instantaneously in 1990, and which, in the absence of the deep ocean effect, would be expected to raise global mean temperature 90% of the way to a new equilibrium (say 2.5 ˚C higher) within about 20 to 30 years. Introduction of the ocean sink could change the estimated time of adjustment to a new equilibrium for the coupled system to anywhere between several hundred and a thousand years.

Important programs of oceanic observations, theory and data analysis are under way. Understanding of critical ocean processes likely will increase dramatically in the next decade, reducing the uncertainty introduced by the present poor understanding of these deep circulations. Nonetheless, because of the complexity of the system and the fundamental limits to observation, the deep ocean circulation (along with clouds) will remain one of the main uncertainties in the climate system, as discussed further in Section 4.

3.3 Economic and Ecological Impacts Over Time

Very little work has yet been done on the estimation of effects under transient simulations of climate change. As already noted, most studies are made on the basis of an assumed CO_2 doubling. The introduction of a time path raises issues that are suppressed in the approach that compares equilibrium states. The costs and benefits of any change depend on how long the change takes to develop (and to be recognized) and how far ahead it will be reliably foreseen. The faster and more surprising the change, the higher will be the economic and environmental effects.

For managed systems, the net effect of any change involves a combination of costs of adaptation and residual damages and benefits. The speed of change matters because it determines how much capital stock (buildings, transport systems, canals, dikes) is rendered obsolete before its time, and how rapidly social patterns must adjust (e.g., through migration). As a practical matter, the time period of predicted climate change (decades to centuries) is long in relation to the useful life of most human-created capital, and thus ample time is available for adaptation through normal capital turnover. Possible differences in the speed of climate change then add only small uncertainty to that already present in the "with vs. without" comparison of equilibrium analyses. The pace of change makes a big difference, of course, when economic effects at different times are aggregated for summary analysis and comparison with mitigation cost. Economic benefits and costs should be discounted, which will give a lower weight to effects in the more distant future.

For unmanaged systems the pace of change may be as important as the ultimate magnitude. Little is known about how ecosystems adapt over time to changing conditions, or how they move geographically as conditions change. For terrestrial ecosystems, studies are under way of the processes by which one ecosystem is replaced by another, what happens at the boundaries, how long the process takes, and how to characterize what is gained, what is lost, and what simply moves (e.g., Smith and Shugart, 1993). But these studies are relatively recent, and the task is difficult. For the next few years, therefore, estimates of impacts over time, even for some given description of the climate change, will remain highly uncertain.

For the ocean, whose complex biogeochemistry and life forms might be influenced by changes over time in coastal seas, water temperature, and winds and open ocean currents, the state is not so much uncertainty but ignorance. As noted earlier, the data gathering and research focused on possible ocean impacts has been small in relation to that devoted to land effects. The potential human cost, if fish stocks were to be influenced, is great for some countries. But there is yet simply no scientific basis for assessing the risk.

3.4 Interactions and Simulation

To analyze the phenomena summarized in Sections 3.1 and 3.2, climate modelers perform so-called “transient” simulations of the global response to greenhouse emissions. Atmospheric GCMs of the type described in Section 2.4 are linked to some (usually highly simplified) noninteractive model of the atmospheric and biospheric chemistry, and to an interactive model of the ocean circulation. Then, fed with a forecast or specification of emissions, these analyses produce an estimate of the variations over time for key climate variables such as regional temperature, precipitation and soil moisture. The coupled ocean-atmosphere models still require massive “flux adjustments” referred to earlier, and the analyses still involve uncertainties as to the scale of climate change (the climate sensitivity), but now we must add the additional uncertainties in the rapidity of the changes.

With the introduction of the complexity of the time-dependent ocean circulation and its coupling to the atmosphere, the predicted sequence of climates turns out to be more uncertain than the climate in some imagined future equilibrium. Further, if proper attention is given to uncertainties in the atmospheric and terrestrial biogeochemistry, importantly including feedbacks from the biosphere and the role (present and future) of the oceanic carbon sink, then the variance in estimates must be considered to be greater still.

Unfortunately, the formal analysis of uncertainty in these coupled systems, in their transient states, is even more sparse than for the calculations of equilibrium climate sensitivity using GCMs coupled to ocean models, and for similar reasons. If an ocean circulation model with reasonable detail is included, a *single* several-century simulation using a coupled ocean-atmosphere model can require a year on the most powerful supercomputer.

Economic costs and benefits accruing at different times should be discounted, which is a process that gives a lower weight to events farther in the future. For example, if the economy can produce a rate of return on resources of 3% per year, then a $100 cost in 2025 is equivalent to a cost of $41 in 1995. This is because a $41 cost today removes productive resources from the economy that would have produced $100 in 30 years. The same procedure holds for economic benefits: $41 received today would grow to be worth as much as a $100 benefit in 2025.

4. LIMITS TO PREDICTABILITY

The discussion above attempts to cover the uncertainty in current analyses of various system components, and of the system as a whole, and to give some idea of when that uncertainty might be substantially resolved. It should be noted, however, that we may encounter immutable limits to prediction, and thus to our ability to lower uncertainty about the effects of greenhouse emissions. One reason, of course, is that it may not prove possible to remove all the problems with the physical, chemical and biological models mentioned above, and the remaining errors may compound to yield uncertainties for some portions of the climate system that are much larger than one would wish for an input to a policy decision. Only time and intensive effort will tell how much reduction can be achieved.

But potentially there are yet more fundamental limits to prediction. First, there may be limits in principle because at some levels of detail the system may be chaotic. The present state of the climate system can be observed only within a limited degree of accuracy, even with the most comprehensive network imaginable. Yet it is possible that paths of climate evolution which differ *initially* by amounts less than this irreducible error may diverge to very different future conditions. In this event the climate is unpredictable even if the climate model is a perfect representation of the physics, chemistry and biology of the planet.

Second, even if aspects of climate are not unpredictable in principle, they may be practically so because of limited knowledge of the current climate. As noted earlier, the temperature and salinity of the deep oceans is not well known, and simulations starting from different definitions of the initial condition of the ocean may lead to results that vary greatly, a situation that could arise even if the climate were not chaotic.

It is known that the chaos associated with weather leads to interannual global average temperature variations of about 0.2 ˚C. How important chaos may be to long-term climate prediction is not yet known, although there are indications that the phenomenon exists on these longer time scales. Specifically, chaos may be evident in some of the fluctuations of temperatures in the northern and southern temperate and polar regions (roughly 45˚ to the Poles), which is revealed by recent studies of Greenland and Antarctic ice cores.

Ice cores contain a valuable nearly continuous record of past climate. The earlier in time the ice was deposited on the Antarctic or Greenland glaciers, the deeper it is now buried. Ice deposited 250,000 years ago lies 2 kilometers deep. Past high-latitude temperatures can be determined from the ice because all water molecules are not identical: they differ in mass and other properties according to the isotopes of hydrogen and oxygen of which they consist. At the point where water freezes to form snow or evaporates, the selection of molecules that make this phase transition differs by type according the temperature. The ice in the cores is compacted snow, and by analyzing its isotopic composition the temperature at polar latitudes can be estimated. Age of the ice is estimated by counting annual layers in the upper portions and isotopic dating, and ice flow modeling in the lower portions.

Figure 6 shows temperature estimates from the present to 250,000 years in the past (Dansgaard, et al., 1993) from the Summit core taken in Greenland and the Vostok core from Antarctica. Readily evident in both hemispheres (particularly the northern) is the stability of the Earth’s temperature in the last 9000 years or so, which was referred to earlier in the discussion. Also, the record shows a high correlation between the northern and southern hemispheres in the long-term movements in temperature, as the Earth has moved in and out of ice ages.

Many natural systems, ranging from the spread of a cloud of milk in a cup of hot tea to the motions of planets, are found to “chaotic.” Chaos is a technical term that describes the fact that, if they include nonlinearities and feedbacks, even simple systems can show an amazing complexity of behavior that cannot be forecast. For dynamical systems, which are those that evolve over time, one implication is that even infinitesimally small differences in starting point can lead to dramatically different conditions in the future. The local weather forecast is an example. We do not have perfect knowledge of the initial conditions, such as the exact temperature at every point in the relevant grid at the instant the forecast is begun. Unfortunately, errors smaller than those from the most comprehensive network can lead to weather forecasts that take completely different courses within one or two weeks. So even with a perfect computer model of the forces driving the weather, a forecast beyond this period is without value *in principle*. Moreover, since weather models are not perfect and the data are not the most accurate imaginable, even the best forecasts are good only for about four to six days.

In addition, over much of the record a curious instability appears in the pattern of temperatures, particularly in Greenland. Repeatedly, temperature has risen or fallen by as much as 10 ˚C in very short periods of time, only a few decades to a century. The process is not understood, although there is a leading hypothesis that credits these swings to changes in the aforementioned thermohaline circulation of the deep-ocean, which is influenced by temperature and precipitation in the far North Atlantic (Manabe and Stouffer, 1993; Nakamura et al., 1994). But whatever the cause, these data point to a natural variability that is characteristic of climate, apart from human emissions or our attempts to mitigate them. Also, to the degree these natural fluctuations are not understood, and cannot therefore be presently forecast, a caveat must be attached to current analyses of the effects of human perturbations of the system.

The potential for chaotic behavior, and the implied limits to our ability to reduce uncertainty

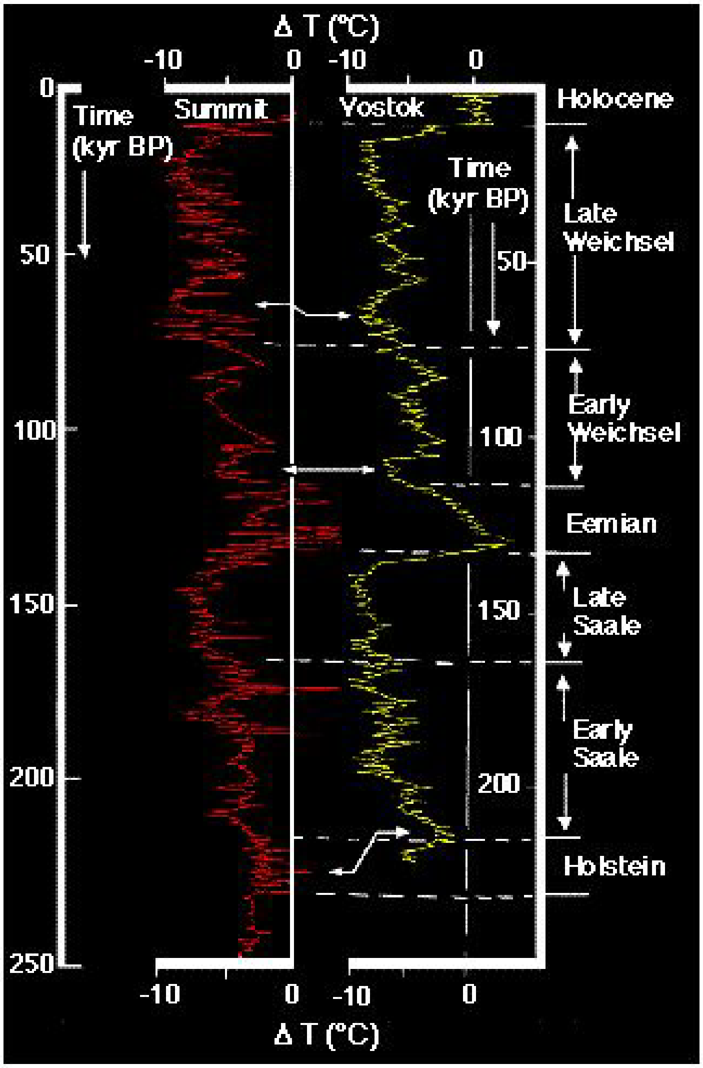

Figure 6. Climate records for the present back to 2500,000 years before present (250 kyrs BP) from Antarctic (Vostok; yellow) and Greenland (Summit; red) ice cores. Shown are temperature differences in degrees centigrade from the present (Holocene) values at each site. (From: Dansgaard et al., 1993.)

about climate change, are very important topics for research. Some parts of the climate system may be more predictable than others (e.g., averages for large regions in contrast to small areas). Or parts of the system may be chaotic but with outcomes that fall within limits that can be defined. Research on this topic, and the planning of the specialized model construction and analysis needed to carry it out, is only beginning. Very likely within a decade or so we will have a better estimate of where the fundamental limits lie, and a clearer impression of how much can, in principle, be achieved in uncertainty reduction.

5. THE POLICY ANALYSIS TASK

The preceding discussion provides no guidance for greenhouse policy, nor was it intended to do so. But it does convey a message about the context within which policy must be formulated, and the demands put on those who would assess alternative mitigation measures.

Regarding the broad policy context, the discussion emphasizes a point made at the outset: neither of the extreme positions, to take urgent action now or do nothing awaiting firm evidence, is a constructive response to the climate threat. Responsible treatment of this issue leads to a difficult position somewhere in between. Furthermore, the policy choices involve balancing future risks against near-term costs. Analysts, and the policymakers and public they serve, will experience little comfort of certainty in their understanding of outcomes, or of convenient thresholds in climate effects, which can help justify policy conclusions. Proposals for adaptation to (uncertain) climate change need to be considered along with (uncertain) mitigation of climate change through emissions reductions. The challenge for policymaking is not unprecedented: many issues have this character. But the scale and complexity of the climate issue, and its large economic stakes,

The implications for analysts who would carry out policy assessment are clear. First, uncertainty is the essence of the issue. Calculations which assume that key uncertain relations can be treated *as if* known with certainty, or which place heavy weight on one or a few simple scenarios, can easily misrepresent both the nature of the problem and the implications of alternative courses of action. A second implication is that groups analyzing the greenhouse issue must take care not to freeze models of the various processes at current levels of knowledge, or to incorporate simplified representations and carry them forward over time without continuing review and reconsideration of their adequacy.

make it especially troublesome for both domestic and international institutions.

The implications for analysts who would carry out policy assessment are more clear. First, uncertainty is the essence of the issue. Calculations which assume that key uncertain relations can be treated *as if* known with certainty, or which place heavy weight on one or a few simple scenarios, can easily misrepresent both the nature of the problem and the implications of alternative courses of action. No doubt it is a difficult task to inform policymakers and the public about the limits to knowledge, and to communicate choices in terms of a balancing of risks. Political leaders seek clear, substantial justification for any action, particularly if it will impose large costs on some or all citizens. Moreover, attempts to improve public understanding of the issue must compete with myriad other social and personal problems demanding attention. Nonetheless, in our view it is the duty of analysts in this area to be faithful to the models and the data, both their strengths and their weaknesses, and to reflect as clearly as possible the attendant uncertainties.

A second implication of this survey is that groups analyzing the greenhouse issue must take care not to freeze models of the various processes at current levels of knowledge, or to incorporate simplified representations and carry them forward over time without continuing review and reconsideration of their adequacy. Understanding of the various aspects of the climate change issue is changing year to year, and even month to month. In some areas, uncertainty is being reduced by research activities; in others new discoveries have the effect of destroying previous understandings and increasing uncertainty.

Unfortunately, keeping up in this area is a unique challenge in its own right, because the expenditure on research in this area is so great and the emerging literature so voluminous. Yet, as emphasized in the discussion above of the way doubled-CO_2 results have been used in policy discussions, it is important that policy analyses not fall far behind the rapidly evolving frontiers of the climate science, the social science, and the work on ecosystems. Policy analysis groups need close working relations with experts in the various contributing disciplines, lest they run the risk of misinforming policymakers and the public on this important issue.

Finally, the discussion highlights the importance of research on improved methods for analyzing uncertainties in policy choice, and (more importantly and more difficult) improved ways to communicate them to a public that is not specialized in the underlying disciplines, but who, on behalf of themselves and their descendants, have a great stake in the outcome.

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