The Greenhouse Effect: Science and Policy

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Global warming from the increase in greenhouse gases has become a major scientific and political issue during the past decade. That infrared radiation is trapped by greenhouse gases and particles in a planetary atmosphere and that the atmospheric CO_2 level has increased by some 25 percent since 1850 because of fossil fuel combustion and land use (largely deforestation) are not controversial; levels of other trace greenhouse gases such as methane and chlorofluorocarbons have increased by even larger factors. Estimates of present and future effects, however, have significant uncertainties. There have also recently been controversial claims that a global warming signal has been detected. Results from most recent climatic models suggest that global average surface temperatures will increase by some 2° to 6°C during the next century, but future changes in greenhouse gas concentrations and feedback processes not properly accounted for in the models could produce greater or smaller increases. Sea level rises of 0.5 to 1.5 meters are typically projected for the next century, but there is a small probability of greater or even negative change. Forecasts of the distribution of variables such as soil moisture or precipitation patterns have even greater uncertainties. Policy responses range from engineering countermeasures to passive adaptation to prevention and a "law of the atmosphere." One approach is to implement those policies now that will reduce emissions of greenhouse gases and have additional societal benefits. Whether the uncertainties are large enough to suggest delaying policy responses is not a scientific question per se, but a value judgment.

WITHIN THE PAST YEAR COVER STORIES OF BOTH *Time* and *Newsweek* have featured global warming from the greenhouse effect and ozone depletion from industrial chemicals. The intense heat, forest fires, and drought of the summer of 1988 and the observation that the 1980s are the warmest decade on record have ignited an explosion of media, public, and governmental concern that the long debated global warming has arrived—and prompted some urgent calls for actions to deal with it. For example, the National Energy Policy Act of 1988 to control carbon dioxide emissions was introduced by Senator Wirth in August 1988, and hearings were held on 11 August. At that hearing, there were sharply conflicting views about whether policy actions are premature given the many remaining scientific uncertainties (*1, 1a*). Whether some amount of scientific uncertainty is "enough" to justify action or delay it is not a scientific judgment testable by any standard scientific method. Rather, it is a personal value choice that depends upon whether one fears more investing present resources as a hedge against potential future change or, alternatively, fears rapid future change descending without some attempt to slow it down or work actively to make adaptation to that change easier. That value choice can only be made efficiently by a society in which those involved in the decision-making process are aware of the nature of the scientific evidence. The public and governmental officials need to know which uncertainties are reducible, which may not be reducible, and how long it might take to narrow the reducible uncertainties. Uncertainties easily reducible in a few years might encourage waiting before implementing policy whereas uncertainties that are unreducible or difficult to reduce might suggest acting sooner. Of course, in the short term new research results may temporarily increase uncertainty, but with major efforts such as the proposed Global Change program, accelerated progress will be more likely (*2*). Therefore, in this article I discuss briefly many of the scientific questions surrounding the greenhouse effect debate. At the end I will turn to the issue of plausible responses.

The greenhouse effect, despite all the controversy that surrounds the term, is actually one of the most well-established theories in atmospheric science. For example, with its dense CO_2 atmosphere, Venus has temperatures near 700 K at its surface. Mars, with its very thin CO_2 atmosphere, has temperatures of only 220 K. The primary explanation of the current Venus "runaway greenhouse" and the frigid Martian surface has long been quite clear and straightforward: the greenhouse effect (*3*). The greenhouse effect works because some gases and particles in an atmosphere preferentially allow sunlight to filter through to the surface of the planet relative to the amount of radiant infrared energy that the atmosphere allows to escape back up to space. The greater the concentration of "greenhouse" material in the atmosphere (Fig. 1) (*4*), the less infrared energy that can escape. Therefore, increasing the amount of greenhouse gases increases the planet's surface temperature by increasing the amount of heat that is trapped in the lowest part of the atmosphere. What is controversial about the greenhouse effect is exactly how much Earth's surface temperature will rise given a certain increase in a trace greenhouse gas such as CO_2.

Two reconstructions of Earth's surface temperature for the past century (Fig. 2) have been made at the Goddard Institute for Space Studies (GISS) and Climatic Research Unit (CRU). Although some identical instrumental records were used in each study, the methods of analysis were different. Moreover, the CRU results include an ocean data set (*6*). These records have been criticized because a number of the thermometers were in city centers and might have measured a spurious warming from the urban heat island (*7*). In other cases thermometers were moved from cities to airports or up and down mountains, and some other measurements are also unreliable. A critical evaluation of the urban heat island effect suggests that in the United States the data may account for nearly 0.4°C of warming in the GISS record and about 0.15°C warming in the CRU record (*8*). Because the U.S. data from where the urban

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heat island effect might be significant are only a small part of the total, these corrections should not automatically be made to the entire global record. However, even after such corrections for the United States are applied to all of the data, the global data still suggest that 0.5°C warming occurred during the past 100 years. Moreover, the 1980s appear to be the warmest decade on record; 1981, 1987, and 1988 were the warmest years on these records (*5, 6*).

Scientific Issues Surrounding the Greenhouse Effect

It is helpful to break down the set of issues known as the greenhouse effect into a series of stages, each feeding into another, and then to consider how policy questions might be addressed in the context of these more technical stages.

Projecting emissions. Behavioral assumptions must be made in order to project future use of fossil fuels (or deforestation, because this too can impact the amount of CO_2 in the atmosphere—it accounts for about 20% of the recent total CO_2 injection of about 5.5×10^9 metric tons). The essence of this aspect then is social science. Projections must be made of human population, the per capita consumption of fossil fuel, deforestation rates, reforestation activities, and perhaps even countermeasures to deal with the extra CO_2 in the air. These projections depend on issues such as the likelihood that alternative energy systems or conservation measures will be available, their price, and their social acceptability. Furthermore, trade in fuel carbon (for example, a large-scale transfer from coal-rich to coal-poor nations) will depend not only on the energy requirements and the available alternatives but also on the economic health of the potential importing nations (*9*). This trade in turn will depend upon whether those nations have adequate capital resources to spend on energy rather than other precious strategic commodities—such as food or fertilizer as well as some other strategic materials such as weaponry. Total CO_2 emissions from energy systems, for example, can be expressed by a formula termed "the population multiplier" by Ehrlich and Holdren (*10*)

$$\text{Total } CO_2 \text{ emission} = \frac{CO_2 \text{ emission}}{\text{technology}} \times \frac{\text{technology}}{\text{capita}} \times \text{total population size}$$

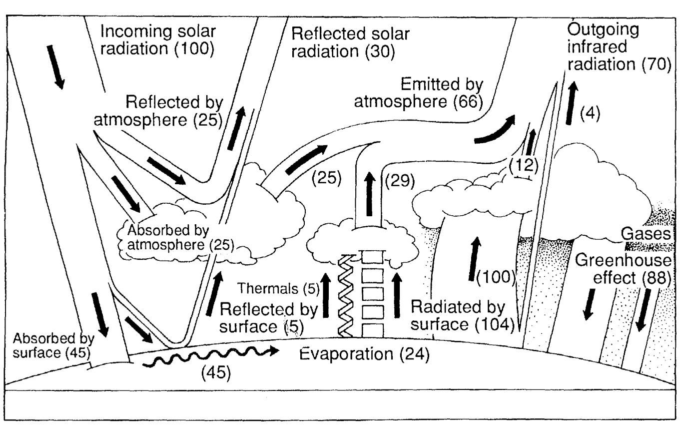

Fig. 1. The greenhouse effect arises because Earth's atmosphere tends to trap heat near the surface. Water vapor, CO_2, and other trace greenhouse gases are relatively transparent to the visible and near-infrared wavelengths that carry most of the energy of sunlight, but they absorb more efficiently the longer, infrared (IR) wavelengths emitted by Earth. Hence an increase in the concentration of greenhouse gases tends to warm the surface by downward reradiation of IR, as shown. (The numbers are given in terms of the percentage each arrow represents relative to Earth-averaged solar constant, about 340 W/m^2.) [Modified from (*4*)]

Table 1. Vulnerability to climate change of water-resource regions of the United States. An asterisk indicates a region is vulnerable to indicated problem [from (*49*)]. Column 2 gives the number of thresholds exceeded in a region; those that are vulnerable to the most problems are listed first.

Basin	Number of thresholds	Vulnerability Category				
		Consumption	Storage	Variability	Hydroelectric	Groundwater
Great Basin	5	*	*	*	*	*
Missouri	4	*		*	*	*
California	4	*	*	*	*	
Arkansas-White-Red	3		*	*		*
Texas-Gulf	3	*		*		*
Rio Grande	3	*		*		*
Lower Colorado	3	*			*	*
Tennessee	2		*		*	
Lower Mississippi	2		*	*		
Upper Colorado	2	*		*		
Pacific Northwest	2		*		*	
Alaska	2		*		*	
Caribbean	2		*	*		
New England	1		*			
Mid-Atlantic	1		*			
South Atlantic-Gulf	1		*			
Great Lakes	1		*			
Ohio	1		*			
Upper Mississippi	1		*			
Souris-Red-Rainy	1			*		
Hawaii	1		*			

The first term represents engineering effects, the second standard of living, and the third demography in this version, which is expanded from the original.

In order to quantify future changes we can make scenarios (such as seen on Fig. 3) that show alternative CO_2 futures based on assumed rates of growth in the use of fossil fuels (*11*). Most typical projections are in the 0.5 to 2% annual growth range for fossil fuel use and imply that CO_2 concentrations will double (to 600 ppm) in the 21st century (*12, 12a*). There is virtually no dispute among scientists that the CO_2 concentration in the atmosphere has already increased by ~25% since ~1850. The record at Mauna Loa observatory shows that concentrations have increased from about 310 to more than 350 ppm since 1958. Superimposed on this trend is a large annual cycle in which CO_2 reaches a maximum in the spring of each year in the Northern Hemisphere and a minimum in the fall. The fall minimum is generally thought to result from growth of the seasonal biosphere in the Northern Hemisphere summer whereby photosynthesis increases faster than respiration and atmospheric CO_2 levels are reduced. After September, the reverse occurs and respiration proceeds at a faster rate than photosynthesis and CO_2 levels increase (*13*). Analyses of trapped air in several ice cores (*14*) suggest that during the past several thousand years of the present interglacial, CO_2 levels have been reasonably close to the preindustrial value of 280 ppm. However, since about 1850, CO_2 has risen ~25%. At the maximum of the last Ice Age 18,000 years ago, CO_2 levels were roughly 25% lower than preindustrial values. The data also reveal a close correspondence between the inferred temperature at Antarctica and the measured CO_2 concentration from gas bubbles trapped in ancient ice (*15*). However, whether the CO_2 level was a response to or caused the temperature changes is debated: CO_2 may have simply served as an amplifier or positive feedback mechanism for climate change—that is, less CO_2, colder temperatures. This uncertainty arises because the specific biogeophysical mechanisms that cause CO_2 to change in step with the climate are not yet elucidated (*16*). Methane concentrations in bubbles in ice cores also show a similar close relation with climate during the past 150,000 years (*17*).

Other greenhouse gases like chlorofluorocarbons (CFCs), CH_4, nitrogen oxides, tropospheric ozone, and others could, together, be as important as CO_2 in augmenting the greenhouse effect, but some of these depend on human behavior and have complicated biogeochemical interactions. These complications account for the large error bars in Fig. 4 (*18*). Space does not permit a proper treatment of individual aspects of each non-CO_2 trace greenhouse gas; therefore I reluctantly will consider all greenhouse gases taken together as "equivalent CO_2." However, this assumption implies that projections for "CO_2" alone (Fig. 3) will be an underestimate of the total greenhouse gas buildup by roughly a factor of 2. Furthermore, this assumption forces us to ignore possible relations between CH_4 and water vapor in the stratosphere, for example, which might affect polar stratospheric clouds, which are believed to enhance photochemical destruction of ozone by chlorine atoms.

Projecting greenhouse gas concentrations. Once a plausible set of scenarios for how much CO_2 will be injected into the atmosphere is obtained the interacting biogeochemical processes that control the global distribution and stocks of the carbon need to be determined. Such processes involve the uptake of CO_2 by green plants (because CO_2 is the basis of photosynthesis, more CO_2 in the air means faster rates of photosynthesis), changes in the amount of forested area and vegetation type, and how CO_2 fertilization or climate change affects natural ecosystems on land and in the oceans (*19*). The transition from ice age to interglacial climates provides a concrete example of how large natural climatic change affected natural ecosystems in North America. This transition represented some 5°C global warming, with as much as 10° to 20°C warming locally near ice sheets. The boreal species now in Canada were hugging the rim of the great Laurentide glacier in the U.S. Northeast some 10,000 years ago, while now abundant hardwood species were restricted to small refuges largely in the South. The natural rate of forest movement that can be inferred is, to order of magnitude, some ~1 km per year, in response to temperature changes averaging ~1° to 2°C per thousand years (*20*). If climate were to change much more rapidly than this, then the forests would likely not be in equilibrium with the climate; that is, they could not keep up with the fast change and would go through a period of transient adjustment in which many hard-to-predict changes in species distribution, productivity, and CO_2 absorptive capacity would likely occur (*21*).

Furthermore, because the slow removal of CO_2 from the atmosphere is largely accomplished through biological and chemical processes in the oceans and decades to centuries are needed for equilibration after a large pertubation, the rates at which climate change modifies mixing processes in the ocean (and thus the CO_2 residence time) also needs to be taken into account. There is considerable uncertainty about how much newly injected CO_2 will remain in the air during the next century, but typical estimates put this so-called "airborne fraction" at about 50%. Reducing CO_2 emissions could initially provide a bonus by allowing the reduction of the airborne fraction, whereas increasing CO_2 emissions could increase the airborne fraction and exacerbate the greenhouse effect (*22*). However, this bonus might last only a decade or so, which is the time it takes for the upper mixed layer of the oceans to mix with deep ocean water. Biological feedbacks can also influence the amount of CO_2 in the air. For example, enhanced photosynthesis could reduce the buildup rate of CO_2 relative to that projected with carbon cycle models that do not include such an effect (*23*). On the other hand, although there is about as much carbon stored in the forests as there is in the atmosphere, there is about twice as much carbon stored in the soils in the form of dead organic matter. This carbon is slowly decomposed by soil microbes back to CO_2 and other gases. Because the rate of this decomposition depends on temperature, global warming from increased greenhouse gases could cause enhanced rates of microbial decomposition of necromass (dead organic matter) (*24*), thereby causing a positive feedback that would enhance CO_2 buildup. Furthermore, considerable methane is trapped below frozen sediments as clathrates in tundra and off

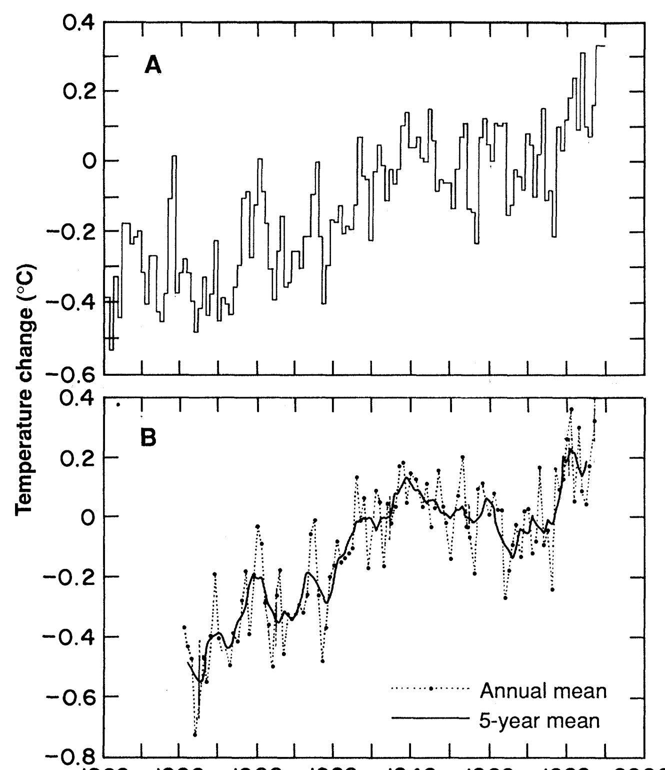

Fig. 2. A comparison of the global surface temperature trends of the past 100 years constructed from land and island stations and ocean surface temperature data sets at the (**A**) Climatic Research Unit and from a similar set of stations (minus the ocean surface temperature data set) at the (**B**) Goddard Institute for Space Studies. [Modified from (*5, 6*)]

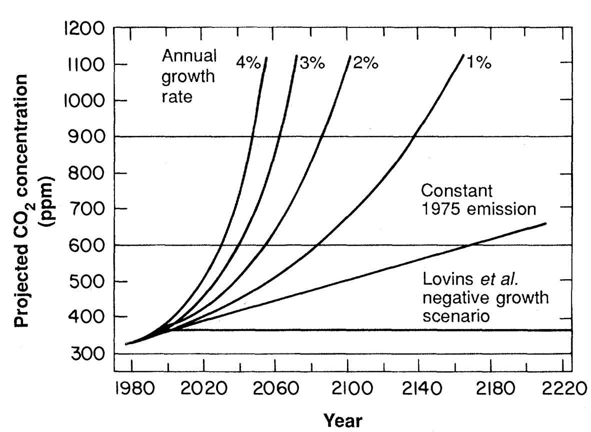

Fig. 3. The extent to which CO_2-induced climatic change will prove significant in the future depends, of course, on the rate of injection of CO_2 into the atmosphere. This depends, in turn, on behavioral assumptions as to how much fossil fuel burning will take place (biospheric effects are neglected in this graph). Since the end of World War II, a world energy growth rate of about 5.3% per year occurred until the mid-1970s, the time of the OPEC price hikes. Rates have come down substantially since then. The figure shows projected CO_2 concentrations for different annual growth rates in fossil energy use, including one for the assumption that no increase in fossil energy use occurs (constant 1975 emission) and even a "negative growth scenario" in which energy growth after 1985 is assumed to be reduced by a fixed amount [0.2 terra watts (TW) per year, which is about 2% of present demand] each year. [Modified from (*11*)]

continental shelves. These clathrates could release vast quantities of methane into the atmosphere if substantial Arctic warming were to take place (*17, 25*). Already the ice core data have shown that not only has CO_2 tracked temperature closely for the past 150,000 years, but so has methane, and methane is a significant trace greenhouse gas which is some 20 to 30 times more effective per molecule at absorbing infrared radiation than CO_2. Despite these uncertainties, many workers have projected that CO_2 concentrations will reach 600 ppm sometime between 2030 and 2080 and that some of the other trace greenhouse gases will continue to rise at even faster rates.

Estimating global climatic response. Once we have projected how much CO_2 (and other trace greenhouse gases) may be in the air during the next century or so, we have to estimate its climatic effect. Complications arise because of interactive processes; that is, feedback mechanisms. For example, if added CO_2 were to cause a temperature increase on earth, the warming would likely decrease the regions of Earth covered by snow and ice and decrease the global albedo. The initial warming would thus create a darker planet that would absorb more energy, thereby creating a larger final warming (*26, 27*). This scenario is only one of a number of possible feedback mechanisms. Clouds can change in amount, height, or brightness, for example, substantially altering the climatic response to CO_2 (*28*). And because feedback processes interact in the climatic system, estimating global temperature increases accurately is difficult; projections' of the global equilibrium temperature response to an increase of CO_2 from 300 to 600 ppm have ranged from ~1.5° to 5.5°C. (In the next section the much larger uncertainties surrounding regional responses will be discussed.) Despite these uncertainties, there is virtually no debate that continued increases of CO_2 will cause global warming (*29–30*).

We cannot directly verify our quantitative predictions of greenhouse warming on the basis of purely historical events (*31*); therefore, we must base our estimates on natural analogs of large climatic changes and numerical climatic models because the complexity of the real world cannot be reproduced in laboratory models. In the mathematical models, the known basic physical laws are applied to the atmosphere, oceans, and ice sheets, and the equations that represent these laws are solved with the best computers available (*32*). Then, we simply change in the computer program the effective amount of greenhouse gases, repeat our calculation, and compare it to the "control" calculation for the present Earth. Many such global climatic models (GCMs) have been built during the past few decades, and the results are in rough agreement that if CO_2 were to double from 300 to 600 ppm, then Earth's surface temperature would eventually warm up somewhere between 1° and 5°C; the most recent GCM estimates are from 3.5° to 5.0°C (*27, 33*). For comparison, the global average surface temperature (land and ocean) during the Ice Age extreme 18,000 years ago was only about 5°C colder than that today. Thus, a global temperature change of 1° to 2°C can have considerable effects. A sustained global increase of more than 2°C above present would be unprecedented in the era of human civilization.

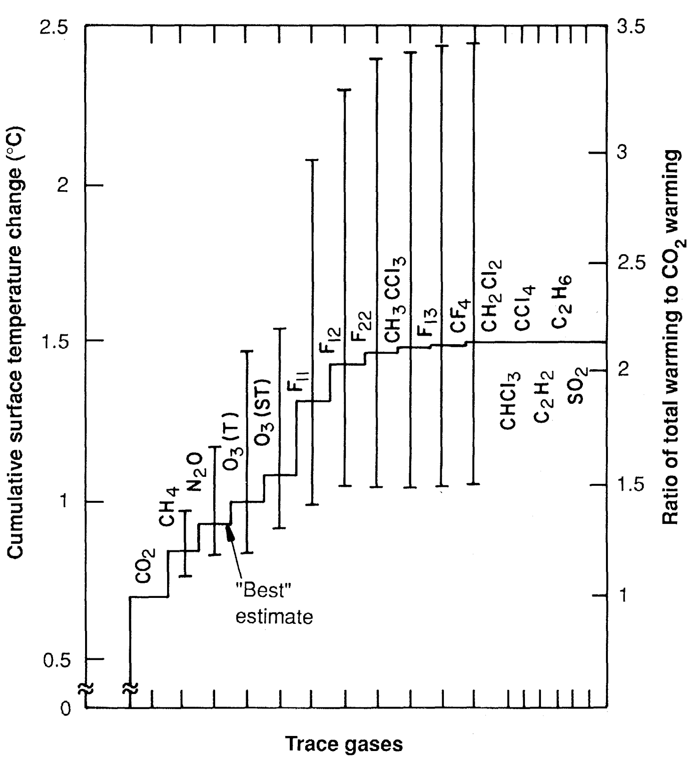

Fig. 4. Various trace "greenhouse gases" contribute about as much to equilibrium global warming (see right-hand scale) as CO_2 for the "best" estimate case, but uncertainties in the projected scenarios of these trace gases are large (see vertical bars). Additional uncertainties in equilibrium temperature response from climate model assumptions are not included in the figure. [Modified from (*18*)]

The largest uncertainty in estimating the sensitivity of Earth's surface temperature to a given increase in radiative forcing arises from the problem of parameterization. Because the equations that are believed to represent the flows of mass, momentum, and energy in the atmosphere, oceans, ice fields, and biosphere cannot be solved analytically with any known techniques, approximation techniques are used in which the equations are discretized with a finite grid that divides the region of interest into cells that are several hundred kilometers or more on a side. Clearly, critically important variables, such as clouds, which control the radiation budget of Earth, do not occur on scales as large as the grid of a general circulation model. Therefore, we seek to find a parametric representation or parameterization that relates implicitly the effects of important processes that operate at subgrid-scale but still have effects at the resolution of a typical general circulation model. For example, a parameter or proportionality coefficient might be used that describes the average cloudiness in grid cell in terms of the mean relative humidity in that cell and some other measures of atmospheric stability. Then, the important task becomes validating these semiempirical parameterizations because at some scale, all models, no matter how high resolution, must treat subgrid-scale processes through parameterization.

Projecting regional climatic response. In order to make useful estimates of the effects of climatic changes, we need to determine the regional distribution of climatic change. Will it be drier in Iowa in 2010, too hot in India, wetter in Africa, or more humid in New York; will California be prone to more forest fires or will Venice flood? Unfortunately, reliable prediction of the time sequence of local and regional responses of variables such as temperature and rainfall requires climatic models of greater complexity and expense than are currently available. Even though the models have been used to estimate the responses of these variables, the regional predictions from state-of-the-art models are not yet reliable.

Although there is considerable experience in examining regional changes [for example, Fig. 5 (*34*)], considerable uncertainty remains over the probability that these predicted regional features will occur. The principal reasons for the uncertainty are twofold: the crude treatment in climatic models of biological and hydrological processes (*35*) and the usual neglect of the effects of the deep oceans (*36*). The deep oceans would respond slowly—on time scales of many decades to centuries—to climatic warming at the surface, and also act differentially (that is, nonuniformly in space and through time). Therefore, the oceans, like the forests, would be out of equilibrium with the atmosphere if greenhouse gases increase as rapidly as typically is projected and if climatic warming were to occur as fast as 2° to 6°C during the next century. This typical projection, recall, is 10 to 60 times as fast as the natural average rate of temperature change that occurred from the end of the last Ice Age to the present warm period (that is, 2° to 6°C warming in a century from human activities compared to an average natural warming of 1° to 2°C per millennium from the waning of the Ice Age to the establishment of the present interglacial epoch) (*37*). If the oceans are out of equilibrium with the atmosphere, then specific regional forecasts like that of Fig. 5 will not have much credibility until fully coupled atmosphere-ocean models are tested and applied (*38*). The development of such models is a formidable scientific and computational task and is still not very advanced.

Validation of climatic model forecasts. Of course, it is appropriate to ask how climatic models' predictions of unprecedented climatic change beyond the next several decades might be verified. Can society make trillion dollar decisions about global economic developments based on the projections of these admittedly dirty crystal balls? How can models be verified?

The first verification method is checking the ability of a model to simulate today's climate. Reproduction of the seasonal cycle is one critical test because these natural temperature changes are several times larger, on a hemispheric average, than the change from an ice age to an interglacial period or a projected greenhouse warming. Also, "fast physics" such as cloud parameterizations can be tested by seasonal simulations or weather forecasts. Global climate models generally map the seasonal cycle well (Fig. 6) (*39*), which suggests that fast physics is not badly simulated on a global basis. However, successful reproduction of these seasonal patterns are not enough that strong validation can be claimed. Precipitation, relative humidity, and the other variables need to be checked. Reproduction of the change in daily variance of these variables with the seasons is another tough test (*40*). The seasonal tests, however, do not indicate how well a model simulates such medium or slow processes as changes in deep ocean circulation or ice cover, which may have an important effect on the decade to century time scales during which the CO_2 concentration is expected to double.

A second verification technique is isolating individual physical components of the model, such as its parameterizations, and testing them against high resolution submodels and actual data at high resolution. For example, one can check whether a parameterized evaporation matches the observed evaporation of a particular cell. But this technique cannot guarantee that the complex interactions of many individual model components are treated properly. The model may predict average cloudiness well but represent cloud feedback poorly. In this case, simulation of overall climatic response to increased CO_2 is likely to be inaccurate. A model should reproduce to better than, say, 25% accuracy the flow of thermal energy between the atmosphere, surface, and space (Fig. 1). Together, these energy flows comprise the well-established energy balance of Earth and constitute a formidable and necessary test for all models.

A third method for determining overall simulation skill is the model's ability to reproduce past climates or climates of other planets. Paleoclimatic simulations of the Mesozoic Era, glacial-interglacial cycles, or other extreme past climates help in understanding the coevolution of Earth's climate with living things. They are valuable for the estimation of both the climatic and biological future (*41*).

Overall validation of climatic models thus depends on constant appraisal and reappraisal of performance in the above categories. Also important are a model's response to such century-long forcings as the 25% increase in CO_2 concentration and different increases in other trace greenhouse gases since the Industrial Revolution.

Most recent climatic models predict that a warming of at least 1°C should have occurred during the past century. The precise "forecast" of the past 100 years also depends upon how the model accounts for such factors as changes in the solar constant or volcanic dust as well as trace greenhouse gases in addition to CO_2 (*42*). Indeed, the typical prediction of a 1°C warming is broadly consistent but somewhat larger than that observed (see Fig. 2). Possible explanations for the discrepancy include (*43*): (i) the state-of-the-art models are too sensitive to increases in trace greenhouse gases by a rough factor of 2; (ii) modelers have not properly accounted for such competitive external forcings as volcanic dust or changes in solar energy output; (iii) modelers have not accounted for other external forcings such as regional tropospheric aerosols from agricultural,

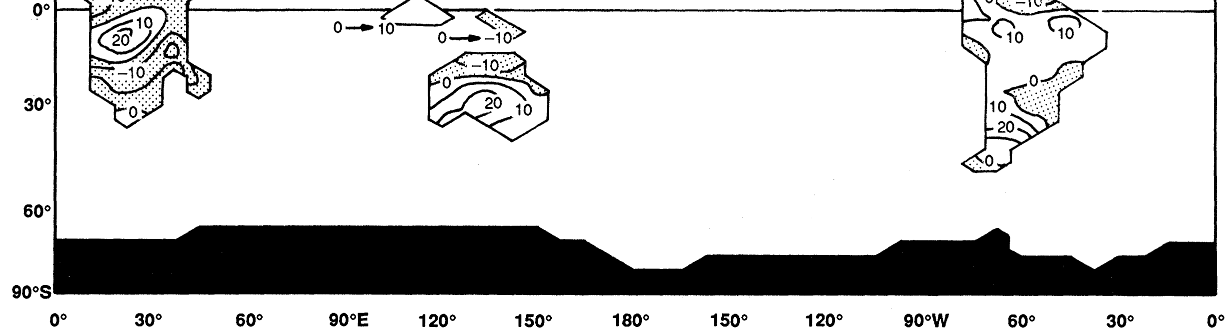

Fig. 5. CO_2-induced change in soil moisture expressed as a percentage of soil moisture obtained from a computer model with doubled CO_2 compared to a control run with normal CO_2 amounts. Note the nonuniform response of this ecologically important variable to the uniform change in CO_2. [Modified from (*34*)]

biological, and industrial activity; (iv) modelers have not properly accounted for internal processes that could lead to stochastic (*44*) or chaotic (*45*) behavior; (v) modelers have not properly accounted for the large heat capacity of the oceans taking up some of the heating of the greenhouse effect and delaying, but not ultimately reducing, warming of the lower atmosphere; (vi) both present models and observed climatic trends could be correct, but models are typically run for equivalent doubling of the CO_2 concentration whereas the world has only experienced a quarter of this increase and nonlinear processes have been properly modeled and produced a sensitivity appropriate for doubling but not for 25% increase; and (vii) the incomplete and inhomogeneous network of thermometers has underestimated actual global warming this century.

Despite this array of excuses why observed global temperature trends in the past century and those anticipated by most GCMs disagree somewhat, the twofold discrepancy between predicted and measured temperature changes is not large, but still of concern. This rough validation is reinforced by the good simulation by most climatic models of the seasonal cycle, diverse ancient paleoclimates, hot conditions on Venus, cold conditions on Mars (both well simulated), and the present distribution of climates on Earth. When taken together, these verifications provide strong circumstantial evidence that the current modeling of the sensitivity of global surface temperature to given increases in greenhouse gases over the next 50 years or so is probably valid within a rough factor of 2. Most climatologists do not yet proclaim that the observed temperature changes this century were caused beyond doubt by the greenhouse effect. The relation between the observed century-long trend and the predicted warming could still be chance occurrences, or other factors, such as solar constant variations or volcanic dust, may not have been accounted for correctly during the past century—except during the past decade when accurate measurements began to be made.

Another decade or two of observations of trends in Earth's climate, of course, should produce signal-to-noise ratios sufficiently high that we will be able to determine conclusively the validity of present estimates of climatic sensitivity to increasing trace greenhouse gases. That, however, is not a cost-free enterprise because a greater amount of change could occur then than if actions were undertaken now to slow down the buildup rate of greenhouse gases.

Scenarios of the environmental impact of CO_2. Given a set of scenarios for regional climatic change we must next estimate the impacts on the environment and society (*46, 47*). Most researchers have focused on the direct effects of CO_2 increases or used model-predicted maps of temperature and rainfall patterns to estimate impacts on crop yields or water supplies (*29a, 30, 48, 49*). Also of concern is the potential that temperature increases will alter the range or numbers of pests that affect plants, or diseases that threaten animals or human health (*50, 50a*). Also of interest are the effects on unmanaged ecosystems, principally forests. For example, ecologists are concerned that the destruction rate of tropical forests attributed to human expansion is eroding the genetic diversity of the planet (*51*). That is, because the tropical forests are in a sense major banks for the bulk of living genetic materials on Earth, the world is losing some of its irreplaceable biological resources through rapid development. Substantial changes in tropical rainfall have been predicted on the basis of climatic models; reserves (or refugia) that are currently set aside as minimal solutions for the preservation of some genetic resources into

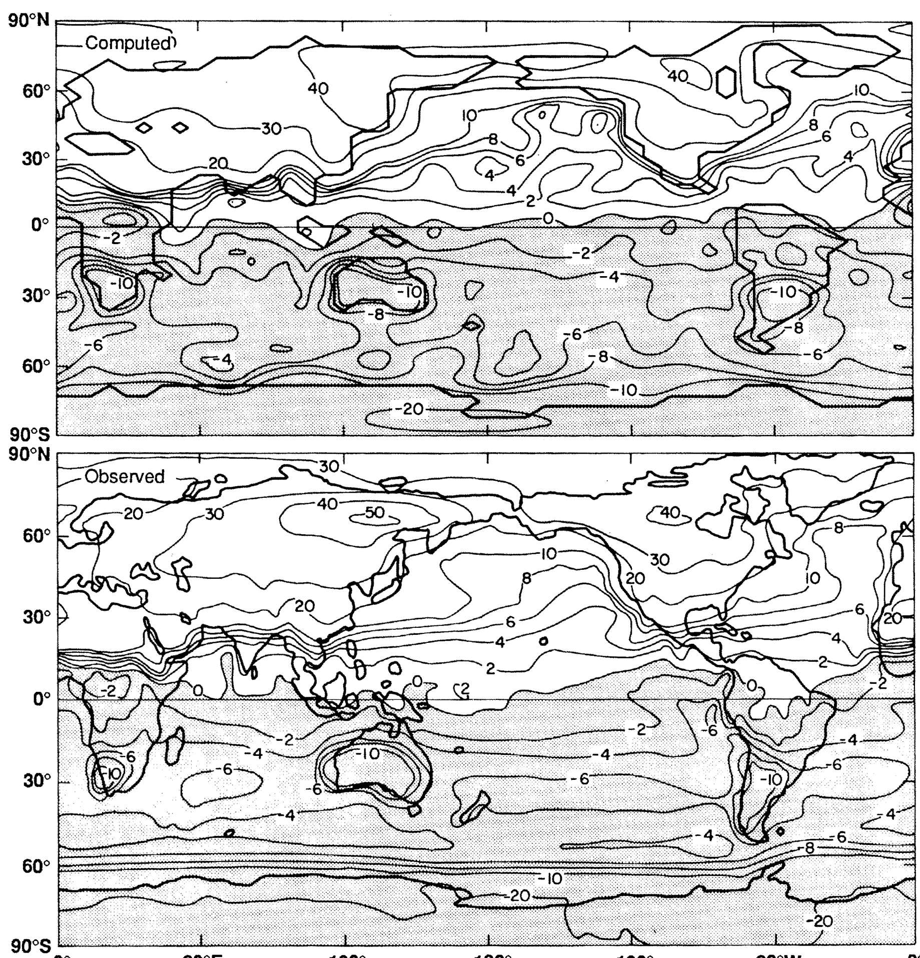

Fig. 6. A three-dimensional climate model has been used to compute the winter to summer temperature extremes all over the globe. The model's performance can be verified against the observed data shown below. This verification exercise shows that the model quite impressively reproduces many of the features of the seasonal cycle. These seasonal temperature differences are mostly larger than those occurring between ice ages and interglacials or for any plausible future carbon dioxide change. Although this approach cannot validate models for processes occurring on medium to long time scales (greater than 1 year), they are very encouraging for validating to a rough factor of 2 such "fast physics" parameterizations like clouds. [Modified from (*39*)]

the future may not even be as effective as currently planned (*52*).

Climate changes resulting from greenhouse gas increases could also significantly affect water supply and demand. For example, a local increase in temperature of several degrees Celsius could decrease runoff in the Colorado River Basin by tens of percent (*25, 48*). A study (*53*) of the vulnerability to climate change of various water resource regions in the United States showed that some regions are quite vulnerable to climatic changes (Table 1).

Water quality will be diminished if the same volume of wastes are discharged through decreased stream flow. In addition, irrigation demand (and thus pressure on ground-water supplies) may increase substantially if temperatures increase without concomitant offsetting increases in precipitation. A number of climate models suggest that temperatures could increase and precipitation decrease simultaneously in several areas, including the central plains of the United States. Peterson and Keller (*54*) estimated the effects of a 3°C warming and a 10% precipitation change on U.S. crop production based on crop water needs. The greatest impact would be in the western states and the Great Plains, less in the Northwest. The warm, dry combination would increase depletion of streams and reduce viable acreage by nearly a third in the arid regions. New supplies of water would be needed, threatening ground water and the viability of agriculture in these regions. On the other hand, farmers in the East, and particularly in the Southeast, might profit if the depletion of eastern rivers were relatively less severe than that in the West or the Plains. However, increases in the efficiency of irrigation management and technological improvements remain achievable, and would help substantially to mitigate potential negative effects. Drying in the West could also markedly increase the incidence of wildfires, which in turn could act as agents of ecological change as climate changes.

Most workers project that an increase in global temperature of several degrees Celsius will cause sea level to rise by 0.5 to 1.5 m generally in the next 50 to 100 years (*55*); such a rise would endanger coastal settlements, estuarine ecosystems, and the quality of coastal fresh water resources (*56, 57*).

Economic, social, and political impacts. The estimation of the distribution of economic "winners and losers," given a scenario of climatic change, involves more than simply looking at the total dollars lost and gained—were it possible somehow to make such a calculation credibly! It also requires looking at these important equity questions: "who wins and who loses?" and "how might the losers be compensated and the winners charged?" For example, if the Cornbelt in the United States were to "move" north and east by several hundred kilometers from a warming, then a billion dollars a year lost in Iowa farms could well eventually become Minnesota's billion dollar gain. Although some macro-economists viewing this hypothetical problem from the perspective of the United States as a whole might see no net losses here, considerable social consternation could be generated by such a shift in climatic resources, particularly since the cause was economic activities (that is CO_2 production) that directed differential costs and benefits to various groups. Moreover, even the perception that the economic activities of one nation could create climatic changes that would be detrimental to another has the potential for disrupting international relations—as is already occurring in the case of acid rain. In essence, what greenhouse gas-induced environmental changes create is an issue of "redistributive justice."

If a soil moisture decrease, such as projected for the United States in Fig. 5 were to occur, then it would have disturbing implications for agriculture in the U.S and Canadian plains. Clearly, present farming practices and cropping patterns would have to change. The more rapidly the climate changed and the less accurately the changes were predicted (which go together), the more likely that the net changes would be detrimental. It has been suggested that a future with soil moisture change like that shown in Fig. 5 could translate to a loss of comparative advantage of U.S. agricultural products on the world market (*58*). Such a scenario could have substantial economic and security implications. Taken together, projected climate changes into the next century could have major impacts on water resources, sea level, agriculture, forests, biological diversity, air quality, human health, urban infrastructure, and electricity demand (*29a, 30, 47, 50, 57, 59*).

Policy responses. The last stage in diagnosing the greenhouse effect concerns the question of appropriate policy responses. Three classes of actions could be considered. First, engineering countermeasures: purposeful interventions in the environment to minimize the potential effects [for example, deliberately spreading dust in the stratosphere to reflect some extra sunlight to cool the climate as a countermeasure to the inadvertent CO_2 warming (*60*)]. These countermeasures suffer from the immediate and obvious flaw that if there is admitted uncertainty associated with predicting the unintentional consequences of human activities, then likewise substantial uncertainty surrounds any deliberate climatic modification. Thus, it is quite possible that the unintentional change might be overestimated by computer models and the intentional change underestimated, in which case human intervention would be a "cure worse than the disease" (*61*). Furthermore, the prospect for international tensions resulting from any deliberate environmental modifications is staggering, and our legal instruments to deal with these tensions is immature (*62*). Thus, acceptance of any substantial climate countermeasure strategies for the foreseeable future is hard to imagine, particularly because there are other more viable alternatives.

The second class of policy action, one that tends to be favored by many economists, is adaptation (*63*). Adaptive strategists propose to let society adjust to environmental changes. In extreme form, some believe in adaptation without attempting to mitigate or to prevent the changes in advance. Such a strategy is based partly on the argument that society will be able to replace much of its infrastructure before major climatic changes materialize, and that because of the large uncertainties, we are better off waiting to see what will happen before making potentially unnecessary investments. However, it appears quite likely that we are already committed to some climatic change based on emissions to date, and therefore some anticipatory steps to make adaptation easier certainly seems prudent (*64*). We could adapt to climate change, for example, by planting alternative crop strains that would be more widely adapted to a whole range of plausible climatic futures. Of course, if we do not know what is coming or we have not developed or tested the seeds yet, we may well suffer substantial losses during the transition to the new climate. But such adaptations are often recommended because of the uncertain nature of the specific redistributive character of future climatic change and because of high discount rates (*65*).

In the case of water supply management, the American Association for the Advancement of Science panel on Climate Change made a strong, potentially controversial, but, I believe, rather obvious adaptive suggestion: governments at all levels should reevaluate the legal, technical, and economic components of water supply management to account for the likelihood of climate change, stressing efficient techniques for water use, and new management practices to increase the flexibility of water systems and recognizing the need to reconsider existing compacts, ownership, and other legal baggage associated with the present water system. In light of rapid climate change, we need to reexamine the balance between private rights and the public good, because water is intimately connected with both. Regional transfers from water-abundant regions to water-deficient regions are often prohibited by legal or economic impediments that need to be examined as part of a hedging strategy for adapting more effectively to the prospect of climatic change even though regional details cannot now be reliably forecast (*66*).

Finally, the most active policy category is prevention, which could take the form of sulfur scrubbers in the case of acid rain, abandonment of the use of chlorofluorocarbons and other potential ozone-reducing gases (particularly those that also enhance global warming), reduction in the amount of fossil fuel used around the world or fossil fuel switching from more CO_2- and SO_2-producing coal to cleaner, less polluting methane fuels. Prevention policies, often advocated by environmentalists, are controversial because they involve, in some cases, substantial immediate investments as insurance against the possibility of large future environmental change, change whose details cannot be predicted precisely. The sorts of preventive policies that could be considered are increasing the efficiency of energy production and end use, the development of alternative energy systems that are not fossil fuel–based, or, in a far-reaching proposal: a "law of the air" proposed by Kellogg and Mead (*67*). They suggest that various nations would be assigned polluting rights to keep CO_2 emissions below some agreed global standard. A "Law of the Atmosphere" was recently endorsed in the report of a major international meeting (*68*).

A Scientific Consensus?

In summary, a substantial warming of the climate through the augmentation to the greenhouse effect is very likely if current technological, economic, and demographic trends continue. Rapid climatic changes will cause both ecological and physical systems to go out of equilibrium—a transient condition that makes detailed predictions tenuous. The faster the changes take place, the less societies or natural ecosystems will be able to adapt to them without potentially serious disruptions. Both the rate and magnitude of typical projections up to 2050 suggest that climatic changes beyond that experienced by civilization could occur. The faster the climate is forced to change, the more likely there will be unexpected surprises lurking (*69*). The consensus about the likelihood of future global change weakens over detailed assessments of the precise timing and geographic distribution of potential effects and crumbles over the value question of whether present information is sufficient to generate a societal response stronger than more scientific research on the problems—appropriate (but self-serving) advice which we scientists, myself included, somehow always manage to recommend (*70*).

High Leverage Actions to Cope with Global Warming

Clearly, society does not have the resources to hedge against all possible negative future outcomes. Is there, then, some simple principle that can help us choose which actions to spend our resources on? One guideline is called the "tie-in strategy" (*71, 72*). Quite simply, society should pursue those actions that provide widely agreed societal benefits even if the predicted change does not materialize. For instance, one of the principal ways to slow down the rate at which the greenhouse effect will be enhanced is to invest in more efficient use and production of energy. More efficiency, therefore, would reduce the growing disequilibrium among physical, biological, and social systems and could buy time both to study the detailed implications of the greenhouse effect further and ensure an easier adaptation. However, if the greenhouse effects now projected prove to be substantial overestimates, what would be wasted by an energy efficiency strategy? Efficiency usually makes good economic sense (although the rate of investment in efficiency does depend, of course, on other competing uses of those financial resources and on the discount rate used). However, reductions in emissions of fossil fuels, especially coal, will certainly reduce acid rain, limit negative health effects in crowded areas from air pollution, and lower dependence on foreign sources of fuel, especially oil. In addition, more energy efficient factories mean reduced energy costs for manufacturing and thus greater long-term product competitiveness against foreign producers (*11, 12a*).

Development of alternative, environmentally safer energy technologies is another example of a tie-in strategy, as is the development and testing of alternative crop strains, trading agreements with nations for food or other climatically dependent strategic commodities, and so forth. However, there would be in some circles ideological opposition to such strategies on the grounds that these activities should be pursued by individual investment decisions through a market economy, not by collective action using tax revenues or other incentives. In rebuttal, a market which does not include the costs of environmental disruptions can hardly be considered a truly free market. Furthermore, strategic investments are made routinely on noneconomic (that is, cost-benefit analyses are secondary) criteria even by the most politically conservative people: to purchase military security. A strategic consciousness, not an economic calculus, dictates investments in defense. Similarly, people purchase insurance as a hedge against plausible, but uncertain, future problems. The judgment here is whether strategic consciousness, widely accepted across the political spectrum, needs to be extended to other potential threats to security, including a substantially altered environment occurring on a global scale at unprecedented rates. Then, the next problem is to determine how many resources to allocate.

If we choose to wait for more scientific certainty over details before preventive actions are initiated, then this is done at the risk of our having to adapt to a larger, faster occurring dose of greenhouse gases than if actions were initiated today. In my value system, high-leverage, tie-in actions are long overdue. Of course, whether to act is not a scientific judgment, but a value-laden political choice that cannot be resolved by scientific methods.

Incentives for investments to improve energy efficiency, to develop less polluting alternatives, control methane emissions, or phase out CFCs may require policies that charge user fees on activities in proportion to the amount of pollution each generates. This strategy might differentially impact less developed nations, or segments of the population such as coal miners or the poor. Indeed, an equity problem is raised through such strategies. However, is it more appropriate to subsidize poverty, for example, through artificially lower prices of energy which distort the market and discourage efficient energy end use or alternative production, or is it better to fight poverty by direct economic aid? Perhaps targeting some fraction of an energy tax to help those immediately disadvantaged would improve the political tractability of any attempt to internalize the external costs of pollution not currently charged to energy production or end use. In any case, consideration of these political issues will be essential if global scale agreements are to be negotiated, and without global scale agreements, no nation acting alone can reduce global warming by more than 10% or so (*73*).

The bottom line of the implications of atmospheric change is that we are perturbing the environment at a faster rate than we can understand or predict the consequences. In 1957, Revelle and Suess (*74*) pointed out that we were undergoing a great "geophysical experiment." In the 30 years since that prophetic remark, CO_2 levels have risen more than 10% in the atmosphere, and there have been even larger increases in the concentrations of methane and CFCs. The 1980s appear to have seen the warmest temperatures in the instrumental record, and 1988 saw a combination of dramatic circumstances that gained much media attention: extended heat waves across most of the United States, intense drought, forest fires in the West, an extremely intense hurricane, and flooding in Bangladesh. Indeed, many people interpreted (prematurely, I believe) these events in 1988 as proof that human augmentation to the greenhouse effect had finally arrived (*75*). Should the rapid warming in the instrumental record of the past 10 years continue into the 1990s, then a vast majority of atmospheric scientists will undoubtedly agree that the greenhouse signal has been felt. Unfortunately, if society chooses to wait another decade or more for certain proof, then this behavior raises the risk that we will have to adapt to a larger amount of climate change than if actions to slow down the buildup of greenhouse gases were pursued more vigorously today. At a minimum, we can enhance our interdisciplinary research efforts to reduce uncertainties in physical, biological, and social scientific areas (*76*). But I believe enough is known already to go beyond research and begin to implement policies to enhance adaptation and to slow down the rapid buildup of greenhouse gases, a buildup that poses a considerable probability of unprecedented global-scale climatic change within our lifetimes.

REFERENCES AND NOTES

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53. P. H. Gleick, in (*48a*).
54. D. F. Peterson and A. A. Keller, in (*48a*).
55. G. de Q. Robin in (*30*); M. F. Meier *et al.*, *Glaciers, Ice Sheets, and Sea Level* (National Academy of Sciences, Washington, DC, 1985). Sea level rises greater than 1.5 m and less than 0.5 m, perhaps even sea level falls, could also occur in the next 50 to 100 years, although most analysts give these extremes low probabilities. Should a much more rapid disintegration of the West Antarctic Ice Sheet than now envisioned occur, sea levels would rise substantially because this glacier has above-ground ice sufficient to raise sea level by ~5 m. On the other hand, because a warming of Antarctica would almost certainly increase snowfall without raising temperatures sufficiently to create summer melt, a doubling of the snowfall over Antarctica could lower sea level perhaps as much as 1 mm per year. Of course, such a change would require that the calving rate in Antarctica does not increase. The same would have to apply for the melting and calving in Greenland, an ice sheet which, unlike Antarctica, has substantial melting at lower altitudes and low-latitude flanks. However, the principal factor responsible for the "most probable" estimate of 0.5- to 1.5-m sea level rise is the assumption that some mountain glaciers will disapper while, at the same time, several degrees Celsius warming of the oceans will, through the direct process of thermal expansion (which is several times greater in warm water than cold water), lead to an inexorable increase in ocean volume and rise of the sea level. A rise of sea level seems highly probable, whereas disintegration of the West Antarctic Ice Sheet or snow accumulation in each Antartica are much more speculative, and such changes will in any case, occur more slowly in response to climate change. Sea level rise only exacerbates the likelihood of catastrophic storm surges especially if warming increases hurricane intensity; K. A. Emanuel, *Nature* **326**, 483 (1987).
56. G. P. Hekstra, in *Proceedings of Controlling and Adapting to Greenhouse Warming* (Resources for the Future, Washington, DC, in press); M. C. Barth and J. G. Titus, Eds., *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation* (Van Nostrand, Reinhold, New York, 1984). The Environmental Protection Agency (EPA), in a comprehensive study of potential scenarios of climate change for the United States (*57*), concluded that building of bulkheads and levies, pumping sand, and raising barrier islands to protect areas against a 1-m rise in sea level by 2100 would cost $73 billion to $100 billion (cumulative capital costs in 1985 dollars). In contrast, elevating beaches, houses, land, and roadways by the year 2100 would cost $50 billion to $75 billion (cumulative capital costs in 1985 dollars) [(*57*), chap. 9].
57. J. B. Smith and D. Tirpak, Eds., *The Potential Effects of a Global Climate Change on the United States*, Draft Report to Congress (Environmental Protection Agency, Washington, DC, October 1988) vol. 2, chap. 9.
58. M. Parry, W. Easterling, P. Crosson, N. Rosenberg, *Resources for the Future Conference Proceedings*, in press; The scenario with the Geophysical Fluid Dynamics Laboratory computer model for soil drying is more severe in central North America than that for other models, such as the Goddard Institute for Space Studies. The agricultural consequences of a number of model scenarios including hypothetical increases in yield resulting from direct CO_2 fertilization and decreases due to heat stress or drought stress are assessed in (*57*). Although no general rules for any crop or region could be determined from the EPA analysis (chap. 10), crop yield changes from a few tens of percent advantages to 50% reductions were obtained. At a minimum, one robust conclusion could be drawn: climate changes of the magnitudes projected in most GCM results for the middle to the late part of the next century certainly will cause major redistribution of cropping zones and farming practices.
59. R. S. Chen, E. M. Boulding, S. H. Schneider, Eds., *Social Science Research and Climate Change: An Interdisciplinary Appraisal* (Reidel, Dordrecht, Netherlands, 1983); The Environmental Protection Agency report (*57*) is the most comprehensive analysis of potential impacts and adaptive strategies and costs, although it was restricted to the United States, and at that, only half a dozen or so regions.
60. M. I. Budyko, *Climatic Changes* (Hydrometeorological Publishers, Leningrad, 1974) (in Russian); C. Marchetti, *Climatic Change* **1**, 59 (1977).
61. S. H. Schneider and L. E. Mesirow, *The Genesis Strategy: Climate and Global Survival* (Plenum, New York, 1976), chap. 7, p. 215.
62. W. W. Kellogg and S. H. Schneider, *Science* **186**, 1163 (1974).
63. K. Meyer-Abich, *Climatic Change* **2**, 373 (1980); L. B. Lave, *International Institute for Applied Systems Analysis, IIASA Rep. CP-81-14* (1981), p. Vi; T. Schelling, in *Changing Climate, Report of the Carbon Dioxide Assessment Committee* (National Academy Press, Washington, DC 1983), p. 449.
64. S. H. Schneider and S. L. Thompson [in *The Global Possible: Resources, Development and the New Century*, R. Repetto, Ed. (Yale Univ. Press, New Haven, 1985), p. 397] call this "anticipatory adaptation".
65. Much of the decision as to whether it is cost effective to wait or act against potential threats depends upon the discount rate used to value potential future losses. For example, S. H. Schneider and R. S. Chen [*Annu. Rev. Energy* **5**, 107 (1980)] described how damage from a sea level rise of 8 m could cost about 1 trillion 1980 dollars some 150 years in the future. At a discount rate of 7% per year, which implies a doubling of an economic investment every 10 years, this hypothesized trillion dollar loss 150 years hence would only be "worth" some $33 million today, less than the value of a single power plant. Although an 8-m rise now seems a low probability, the discounting example remains instructive.
66. In the example of water supplies and climatic change, most of the local policy decisions facing urban water engineers or rural irrigation planners would be easiest to face if we had more credible specific regional forecasts of temperature and precipitation changes (*48*). However, regional details are the most difficult variables to predict credibly. Thus, strategies to build flexibility in adapting to changing climate statistics seem appropriate for local or regional water supply planning. Because of uncertainty over details, an individual planner in a region may face difficulty in choosing exactly how to respond to the advent or prospect of rapid climate change. But this should not necessarily deter strategic hedging at national or international levels. In other words, most local or regional water supply planners would not welcome the prospect of rapidly changing climate. Therefore, most planners would hold that if the rate of climate change could be slowed down and time bought to study the outcomes and to adapt more cheaply that this would be an appropriate recommended national-level strategic response.
67. W. W. Kellogg and M. Mead, *The Atmosphere: Endangered and Endangering* (U.S. Department of Health, Education and Welfare, Washington, DC, 1975).
68. Conference statement, *The Changing Atmosphere: Implications for Global Security*, Toronto, Ontario, Canada, 27 to 30 June 1988 (Environment Canada, Toronto, 1988). The report noted that the "first steps in developing international law and practices to address pollution of the air have already been taken." Several examples are cited in it, in particular the Vienna Convention for the Protection of the Ozone, Air, and Its Montreal Protocol signed in 1987. The report states that "These are important first steps and should be actively implemented and respected by all nations. However, there is no overall convention constituting a comprehensive international framework that could address the interrelated problems of the global atmosphere, or that is directed toward the issues of climate change". It set forth a far-reaching action plan that would have major implications for government, industry, and populations. This report follows on the heels of the United Nations Commission on Environment and Development, known as the Bruntland Commission Report, which argued that environment, development, and security should not be treated as separate issues, but rather as connected problems.

69. W. S. Broecker, testimony for U.S. Senate Subcommittee on Environmental Protection, 28 January 1987.
70. It is important to ask how long it might take the scientific community to be able to provide more credible time-evolving regional climatic anomaly forecasts from increasing greenhouse gases; S. H. Schneider, P. H. Gleick, L. Mearns in (49); Schneider *et al.* suggested that it will be at least 10 years and probably several decades before the current level of scientific effort can provide a widespread consensus on these details. The reason such time is needed at current levels of effort is that providing credible regional details will require the coupling of high resolution atmosphere, ocean, and sea ice models with ecological models that provide accurate fluxes of energy and water between atmosphere and land as well as nutrient cycling and chemical transformations that account for trace greenhouse gas buildup over time. A dedicated effort to accelerate the rate of progress could conceivably speed up the establishment of a consensus on regional issues, but at best 10 years or so will be necessary even with a dramatic effort. However, such efforts would clearly put future decision making on a firmer factual basis and help to make adaptation strategies more effective sooner.
71. The "tie-in" strategy was first formulated by E. Boulding, *et al.* [in *Carbon Dioxide Effects, Research and Assessment Program: Workshop on Environmental and Societal Consequences of a Possible CO_2-induced Climatic Change*, Report 009, CONF-7904143, U.S. Department of Energy (Government Printing Office, Washington, DC, October 1980), pp. 79–103]; it was later adopted by W. W. Kellogg and R. Schware, *Climate Change and Society, Consequences of Increasing Atmospheric Carbon Dioxide* (Westview Press, Boulder, CO, 1981).
72. S. H. Schneider and S. L. Thompson, in *The Global Possible: Resources, Development and the New Century*, R. Repetto, Ed., (Yale Univ. Press, New Haven, 1985), pp. 397–430.
73. J. A. Edmonds, W. B. Ashton, H. C. Cheng, and M. Steinberg (in preparation) have calculated that the U.S. contributes some 5% of CO_2 emissions, but this fraction could drop significantly if it holds emissions growth while other nations with large populations try to catch up with U.S. per capita energy use standards.
74. R. Revelle and H. Suess, *Tellus* **9**, 18 (1957).
75. K. E. Trenberth, G. W. Branstator, P. A. Arkin, *Science* **242**, 1640 (1988); S. H. Schneider, *Climatic Change* **13**, 113 (1988). Clearly, one hot year can no more prove that the greenhouse effect has been detected in the record any more than a few cold ones could disprove it. The 1990s, should they see a continuation of the sharp warming trend of the 1980s, will undoubtedly lead many more scientists to predict confidently that the increase in trace greenhouse gases has caused direct and clearly detectable climatic change. Already a few scientists are satisfied that the effects are 99% detectable in the record. J. Hansen (*1a*); see also, J. N. Wilford *New York Times*, 23 August 1988, p. C4.
76. *Toward an Understanding of Global Change, Initial Priorites for U.S. Contributions to the International Geosphere-Biosphere Program* (National Academy Press, Washington, DC, 1988); S. H. Schneider, *Issues Sci. Technol.* **IV** (no. 3), 93 (1988).
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Research Articles

Mechanism of Interleukin-2 Signaling: Mediation of Different Outcomes by a Single Receptor and Transduction Pathway

MICHAEL A. TIGGES, LESLIE S. CASEY, MARIAN ELLIOTT KOSHLAND

The T cell lymphokine, interleukin-2 (IL-2), plays a pivotal role in an immune response by stimulating antigen-activated B lymphocytes to progress through the cell cycle and to differentiate into antibody-secreting cells. An IL-2 inducible B lymphoma line, in which the growth and differentiation responses are uncoupled, provides a model system for dissecting the signaling mechanisms operating in each response. This system was used to show that both signals are initiated by IL-2 binding to a single, unifunctional receptor complex. Moreover, both signals are transduced by a pathway that does not involve any known second messenger system and that can be blocked by a second T cell lymphokine, interleukin 4. These findings suggest that the pleiotrophic effects of IL-2 are determined by different translations of the signal in the nucleus.

IN A PRIMARY IMMUNE RESPONSE A RESTING B LYMPHOCYTE IS triggered by antigen and T cell lymphokines to proliferate and to differentiate into a pentamer immunoglobulin M (IgM)–secreting cell. Although many of the lymphokines involved in the process have been identified, purified, and cloned, their precise roles in the response and the mechanism of their action have been difficult to define. The difficulties stem in part from the multifunctional nature of the lymphokines. Each can stimulate B cells, T cells, and in some cases accessory cells as well (*1*). Moreover, each lymphokine can deliver multiple signals to the same lymphocyte (*2–4*) and the effects can be enhanced or suppressed in the presence of other lymphokines (*5–8*). Difficulties also stem from the heterogeneity of normal lymphoid populations; even the most highly purified preparations are likely to be contaminated with other cell types, making the assignment of the lymphokine target difficult.

Understanding lymphokine signaling of B cells requires, therefore, a more defined experimental system in which the responses to a single pure lymphokine can be assessed in a cloned population of cells. We have recently developed such a system for analyzing the signals that the T cell lymphokine, interleukin-2 (IL-2), delivers to B cells in a primary immune response (*9*). The system makes use of a murine B cell line (BCL_1 CW13-3B3) that is representative of normal antigen-activated B cells. Like their normal counterparts (*6*), BCL_1 cells express IL-2 receptors and can be induced by IL-2 to assemble and secrete pentamer IgM (*9, 10*). The secretion of IgM is effected by the delivery of a single differentiative signal that activates the gene encoding the pentamer joining component, the J chain (*11*).

Unlike their normal counterparts, the BCL_1 lymphoma cells do not exhibit a proliferative response to IL-2 under the standard

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