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SCIENCE AND NONSCIENCE CONCERNING HUMAN-CAUSED CLIMATE WARMING*

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ABSTRACT

The human-caused global warming problem is now the focus of intense international attention in many sectors of society. As we learn more about the science of the problem, the sense of controversy about the state of the science has actually increased, sharply so over the past decade. This essay highlights the fundamental aspects of the science underlying global warming. The vital roles of climate models and of climate data in sharpening scientific understanding are featured. Finally, the roles of controversy in the science and the sociology of this problem are addressed, and new insights are offered on the inevitability of future major conflicts and controversies as society begins to deal with the need to either reduce the use of fossil fuels considerably or adapt to substantial changes in Earth's climate.

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WHY THIS ESSAY?

I am an atmospheric and climate scientist with a career-long interest in understanding how the climate system works. I centered my earliest research, in the late 1960s, on direct analysis of available observations to isolate the most important mechanisms governing atmospheric behavior. It made me very much aware that the available atmospheric measurements and accompanying atmospheric theory are not sufficient to provide the deep quantitative understanding that is required to predict changes within the climate system. It was already clear to me that mathematical models would have to be added to gain deeper understanding and improved predictive skills.

In 1970, I joined National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University, which was leading the world in the new effort to use mathematical modeling approaches to understand the entire climate system and how it changes. GFDL was attempting to include and understand various parts of the climate system, including such key aspects as the ocean and land-surface systems. My task was to emphasize the stratosphere and the climate effects of atmospheric chemistry, including ozone, a gas that absorbs solar and infrared radiation efficiently. I soon learned that reconciling theory and observations through the use of mathematical models is essentially the only way to achieve a fully quantitative understanding of the climate system. More importantly, I also learned that the challenges to be overcome through the use of mathematical models are daunting, requiring the efforts of dedicated teams working a decade or more on individual aspects of the climate system.

It is this high degree of difficulty and complexity that provides significant context for this personal essay on human-caused "greenhouse warming"[2] and some of its broader implications. The climate system is sufficiently complex and all encompassing that there are no "all-knowing" experts on this problem. However, teams of talented scientists working together can, and do, become close to the equivalent of an encompassing expertise. I am fortunate to be surrounded at GFDL by a team of world-renowned scientists who are knowledgable about almost all aspects of greenhouse warming. Most of the insights I

[2] In this article, the term greenhouse warming is used to describe the general warming of Earth's climate in response to human-produced emissions of carbon dioxide and other greenhouse gases such as methane, nitrous oxide, and the chlorofluorocarbons.

offer have been gained from a research lifetime of fruitful encounters with this extraordinary group of colleagues.

AN OVERVIEW OF THE SCIENCE OF GLOBAL WARMING

Historical Setting

Since the famous work of Arrhenius in 1896 (1), the possibility of a net warming of the global climate due to increases in atmospheric carbon dioxide (CO_2) produced by the burning of fossil-fuel has been recognized. The subject matured with the publication in 1967 by Manabe & Wetherald (2) of the first fully self-consistent model calculation of this greenhouse warming effect. They used a simple one-dimensional (altitude only) model of the global atmosphere. In the three decades since, a tremendous amount of observational, theoretical, and modeling research has been directed at the climate system and possible changes in it due to human activity. This research strongly demonstrates that potential climate changes are projected to occur that are well worth our collective attention and concern.

This considerably strengthened climate knowledge base has energized proposals for aggressive international efforts to mitigate the impact of greenhouse warming by substantially reducing the use of fossil fuels to supply the world's growing need for energy. However, that same research effort has shown that, in projecting future climate changes, remaining scientific uncertainties are significant. These uncertainties are regarded by many as good reason to be extremely cautious in implementing any policies designed to reduce CO_2 emissions. Others, however, argue that the risks of inaction are very large and that the scientific uncertainties include the possibility that the greenhouse warming problem could well be worse than current best estimates. Thus, serious policy disagreements can be amplified by differing perspectives on the current state of greenhouse warming science.

Some Fundamental Aspects of Greenhouse Warming Science

The earth is strongly heated every day by incoming radiation from the sun. This heating is offset by an equally strong infrared radiation leaving the planet. Interestingly, if Earth were without any atmosphere, and if its surface reflectivity did not change, global-mean surface temperature would be roughly 33°C colder than it is today. This large difference is due to the strong atmospheric absorption of infrared radiation leaving the earth's surface. The major atmospheric infrared absorbers are clouds, water vapor, and CO_2. This strong infrared absorption (and strong reemission) effect is extremely robust: It is readily measured in the laboratory and is straightforwardly measured from earth-orbiting satellites.

Simply put, adding CO_2 to the atmosphere adds another "blanket" to the planet and, thus, directly changes the heat balance of the earth's atmosphere.

Individuals skeptical about the reality of global warming have correctly noted that, in terms of direct trapping of outgoing infrared radiation, water vapor is by far the dominant greenhouse gas on earth. Since water vapor dominates the current radiative balance, how can it be that CO_2 is anything other than a minor contributor to earth's absorption of infrared radiation? Part of the answer comes from the well-known modeling result from infrared spectroscopy that net planetary radiative forcing changes roughly linearly in response to logarithmic changes in CO_2.[3] Thus, a quadrupling of CO_2 gives another roughly 1°C direct warming over the direct 1°C warming for a CO_2 doubling, valid for the extreme assumption that water vapor mixing ratios[4] and clouds do not change. Interestingly, this approximate relationship also holds for a large extended range as CO_2 is decreased (see footnote 3).

It is thus hard to escape the conclusion that CO_2 provides a measurable direct addition to the atmospheric trapping of infrared radiation leaving the surface of our planet. However, a simple comparison of the relative greenhouse efficiencies of water vapor and CO_2 quickly becomes problematic because water vapor enters the climate system mostly as a "feedback" gas. All models and observations currently indicate that as climate warms or cools, to a pretty good approximation, the observed and calculated global-mean relative humidity of water vapor remains roughly constant as the climate changes, whereas its mixing ratio does not.[5] Thus, as climate warms (cools), the holding capacity of atmospheric water vapor increases (decreases) exponentially. This is a powerful

[3]Scientists at GFDL recently performed simple one-dimensional radiative/convective model calculations of the effects of reducing CO_2. The log-linear relationship has been found to hold down to CO_2 concentrations to as low as one sixty-fourth of preindustrial levels. As CO_2 is decreased, the atmosphere's ability to hold water vapor collapses and the global temperatures drop sharply.

[4]Relative humidity is the ratio (in percentage) of the vapor pressure of air to its saturation vapor pressure. The saturation vapor pressure of air, determined from the Clausius-Claperon equation of classical thermodynamics, is a strong exponential function of temperature, roughly doubling for each 10°C. Water vapor mixing ratio is the mass of water vapor of air divided by the mass of dry air; it is generally conserved for a few days following an air parcel when no condensation is present.

[5]Relative humidity (see footnote 3) is determined in the troposphere by the interplay among evaporation at the earth's surface, upward transfer of water vapor (by small-scale turbulence, thunderstorm-scale moist convection, large-scale rising motion), and net removal by precipitation. Equally important is the local lowering of relative humidity in the troposphere due to adiabatic warming in regions of descending air under approximate conservation of water vapor mixing ratio. Any appeal to a sharp change in mean relative humidity thus necessarily hypothesizes a substantial change in the dynamical behavior of the troposphere, in this case a large change in the motions of the troposphere in response to a comparatively small perturbation to the thermodynamics of the climate system.

water vapor positive feedback mechanism—that is, a process that acts to amplify the original warming caused by increasing CO_2 levels. With this major positive feedback, the modeled "climate sensitivity"[6] increases by about a factor of three, to roughly 3°C. Lindzen (3) hypothesized that this water vapor feedback effect could actually be negative in the upper troposphere. If this were the case, then the water vapor positive feedback amplifying effect would be roughly one third to one half less than that currently projected. A conceptual difficulty with making this hypothesis work is that the relative humidity of the upper troposphere must then get sharply and progressively lower as the lower troposphere warms up and moistens in response to the added infrared absorbers. Conversely, the relative humidity of the upper troposphere must get progressively higher if something were acting to cool the planet. In effect, this hypothesis states that the dynamical behavior of the atmosphere would change strongly in response to altered infrared absorbers (see Footnote 4). Currently, observational evidence remains generally consistent with the modeling results that project a strong positive water vapor mixing ratio feedback under approximate constancy of relative humidity as the climate changes (4, 5). The quality of water vapor data in the upper troposphere, however, is not particularly good, and none of the current observational tests can definitively address the issue at hand—how the water vapor feedback might work a century from now.

The basic story of human-induced greenhouse warming remains simple. Increased infrared absorptivity due to increasing CO_2 and other trace gases produces a net heating effect on the earth's surface, due mainly to increased downward infrared radiation. The effect is not dissimilar to the suppression of nighttime cooling when there is cloud cover or a very humid weather pattern. The positive feedback effect of water vapor acts to amplify the warming effect, both locally and globally.

An additional, but smaller, positive feedback is the relationship between ice (or its absence) at the earth's surface and its reflectivity (albedo) of solar radiation. In essence, if ice or snow cover melts, the surface left exposed (ground, vegetation, or water) is generally less reflective of incoming solar radiation. This leads to more absorption of the solar radiation, thus more warming, less ice, and so on.

Inclusion of this "ice-albedo" feedback process in mathematical models of the climate amplifies further the calculated warming response of the climate to increased concentrations of CO_2 and infrared absorbing gases; it also amplifies any calculated cooling. Other kinds of feedbacks, both positive and negative,

[6]The term climate sensitivity typically refers to the level of equilibrium global-mean surface air temperature increase that the climate system would experience in response to a doubling of CO_2. Each model has its own climate sensitivity, almost guaranteed to be somewhat different from the unknown value for the real world.

result from interaction of land surface properties (e.g. changes of vegetation that lead to albedo and evaporation changes) with climate warming/cooling mechanisms or from changes in CO_2 uptake by the biosphere.

The major source of uncertainty in determining climate feedback concerns the impact of clouds on the radiative balance of the climate system.[7] A CO_2-induced increase in low clouds mainly acts to reflect more solar radiation and thus would provide a negative feedback to global warming. An increase in high clouds mainly adds to the absorption of infrared radiation trying to escape the planet and would thus provide a positive feedback. A change in cloud microphysical and optical properties could go either way. Which of these would dominate in an increasing-CO_2 world? We are not sure. Our inability to answer this question with confidence is the major source of uncertainty in today's projections of how the climate would respond to increasing infrared-absorbing gases. Furthermore, it is not likely this cloud-radiation uncertainty will be sharply reduced within the next 5 years, no matter what promises are offered, expectations are stated, or claims are made.

Although clouds dominate the climate modeling uncertainty, other key processes are also in need of improved understanding and modeling capability. An example is the effect of human-produced airborne particulates (aerosols) composed mostly of sulfate (from oxidation of the sulfur in fossil fuels) and carbon (from open fires). Sulfate aerosols are mostly reflective of solar radiation, producing a cooling effect, whereas carbonaceous aerosols mostly absorb solar radiation, producing a net heating effect. Efforts to reduce the current uncertainty are limited by inadequate measurements. Even more uncertain are the so-called indirect effects of atmospheric aerosols. By indirect effect we mean the uncertain role the presence of these aerosols plays in the determination of cloud amounts and their optical properties.

Another key uncertainty lies in modeling the response of the ocean to changed greenhouse gases. This affects the calculated rate of response of the climate over, say, the next century, as well as the possibility of changed ocean circulation, a potential major factor in shaping regional climate changes.

A frequently overlooked aspect of the human-caused greenhouse warming problem is its fundamentally very long timescales. The current rate of adding to the CO_2 concentrations of the atmosphere is a bit more than half a percent per year. Thus, the time required for CO_2 amounts to approach twice preindustrial levels is roughly a century or so, a process well underway (now about 30% higher). Also, the climate is not expected to respond quickly to the added

[7]Clouds are effective absorbers and reflectors of solar (visible plus ultraviolet) and infrared radiation. Their net effect is to cool the planet, but the effect is very small relative to the 33°C "atmosphere/no atmosphere" difference noted above. However, for predicting smaller human-caused climate changes, the effect of clouds becomes crucially important.

CO_2 because of the large thermal inertia of the oceans. This effect can produce delays in the realized warming on timescales ranging from decades to centuries. Moreover, the deep ocean carries over a thousand years of thermal "memory." Thus, it will take a long time for this problem to reach its full potential.

This great inertia in the climate is also a big factor at the other end of the problem. What if we get a climate we do not like and want our "normal" one back? Currently, the apparent net atmospheric lifetime of fossil-fuel–produced CO_2 is about three quarters of a century. Thus, the natural drawdown of the extra CO_2 would take a long time. Also, the gradually warmed ocean would take a long time to give up its accumulated heat in a climate that had been given a chance to return toward its essentially undisturbed state.

WHY CLIMATE MODELS ARE IMPERFECT AND WHY THEY ARE CRUCIAL ANYWAY

Over the past three decades, a quiet revolution has fundamentally changed the way that much of the research in climate science works. Earlier, the controlling science paradigm was the interchange between theory and observation concerning the structure and behavior of natural phenomena. Today, much climate research is driven by the interactions among theory, observation, and modeling. By modeling, we mean computer-based simulations of various phenomena based on numerical solutions of the theory-based equations governing the phenomena under investigation. These combined approaches are now widespread in the physical sciences. It is significant that mathematical modeling of weather and climate literally pioneered this new approach to scientific research.

Mathematical models of climate can range from simple descriptions of simple processes to full-blown simulations of the astoundingly complex climate system. Models of the coupled atmosphere-ocean-ice-land system lie close to the most complex limit of such models. This very complexity of climate models can lead to highly divergent human reactions to them, varying from "garbage in, garbage out" to almost worshipful. The truth is far from either of these unscientific characterizations.

Newcomers to the greenhouse warming problem tend to be unaware of the long and rich history of mathematical modeling of the atmosphere and the ocean. In the late 1940s and early 1950s, simple mathematical models were created to attack the weather forecasting problem. More advanced models were built in the late 1950s and early 1960s (6, 7) because of a strong research interest in understanding the circulation of the atmosphere. Shortly thereafter, the first model bearing a strong resemblance to today's atmospheric models was created (8). That early model, as well as all of today's models, solves the equations of classical physics relevant for the atmosphere, ice, ocean, and land surface. These equations are conservation of momentum (Newton's second law of motion), conservation of heat (first law of thermodynamics), and conservation of matter (air, water, chemicals, etc, can be blown around by wind or currents, changed in phase, transferred across boundaries, or converted chemically, but the number of atoms of each kind remains unchanged).

The modeling approach thus provides high potential for fundamental tests of applications of these theoretical first principles. Such modeling appears deceptively simple: These equations are taught in high school physics. There are some daunting challenges, however. When coupled and applied to moving (and deforming) fluids such as air and water, these equations form continuum systems that are intrinsically nonlinear and can exhibit surprisingly counterintuitive behaviors. Moreover, their solution in a climate model requires a reasonably fine-scale grid of computational points all over the atmosphere-ice-ocean-land surface system. In addition, important small-scale processes such as moist convection (e.g. thunderstorms) and turbulent dissipation remain formidably difficult to incorporate on a first-principles basis. Worse, no meaningful steady-state solutions solve directly for the average climate. In effect, the average climate in such a model must be described as a statistical equilibrium state of an unstable system that exhibits important natural variability on timescales of hours (thunderstorms), days (weather systems), weeks to months (planetary-scale waves/jet-stream meanders), years (El Niño), and decades to centuries (ocean circulation variations and glacial ice changes). Clearly, models of such a large and complex system are intrinsically computer intensive. Fortunately, today's supercomputers are over a thousand times faster than those of 30 years ago. Because of today's widespread availability of relatively inexpensive computer power, the number of fully coupled atmosphere-ocean climate models in the world has increased from a few in the early 1980s to roughly 10 independently conceived models today. Roughly 20 more are essentially based on these 10 models.

Over the last half century, use of these kinds of physically based mathematical models has resulted in major improvements in the science of weather forecasting. Sharp skill improvements have been achieved in finding the useful short-term predictability in a fundamentally chaotic system (by which I mean that the details of weather variations become essentially unpredictable after a sufficient lapse of time, say a couple of weeks) (9). For example, it has become almost routine to forecast the intensity and path of a major winter storm system well before the surface low-pressure area (so ubiquitously displayed in television weathercasts) has even formed.

Recently, it has become clear that slower variations of the coupled ocean-ice-atmosphere-land surface system provide potential for finding useful predictability on timescales longer than the couple of weeks characteristic of individual weather systems. The most visible example is the realization that El Niño events, which produce warming in the tropical eastern Pacific Ocean, may be predictable a year or so in advance under certain circumstances (10). The existence of such a "predictable spot" of warm ocean suggests a "second-hand" improvement of prediction of seasonal weather anomalies (e.g. a wetter-than-normal California winter).

The existence of such extended-range predictive potential in the climate system leads to obvious questions about such models' validity for predicting systematic changes in the statistical equilibrium climate (say a 20-year running average) resulting from the inexorably increasing infrared-active gases that are currently underway. First, we must recognize that these are conceptually quite different things: Weather forecasting attempts to trace and predict specific disturbances in an unstable environment; climate projections attempt to calculate the changed statistical equilibrium climate that results from applying a new heating mechanism (e.g. CO_2 infrared absorption) to the system. Perhaps surprisingly, predicting the latter is in many respects simpler than predicting the former.

As an example of the fundamental difference between weather forecasting and climate change, consider the following simple and do-able "lab" thought experiment that utilizes the common pinball machine.[8] As the ejected ball in the pinball machine careens through its obstacle-laden path toward its inevitable demise in the gutter, its detailed path, after a couple of collisions with the bumpers, becomes deterministically unpredictable. Think of this behavior as the "weather" of the pinball machine. Of course, the odds against success can be changed dramatically in favor of the player by raising the level of the machine at the gutter end, in effect changing the "climate" of the pinball machine. By reducing the slope of the playing field, the effective acceleration of gravity has been reduced, increasing the number of point-scoring collisions before the still inevitable final victory of gravity. Interestingly, in this altered pinball machine "climate," the individual trajectories of the balls are ultimately as unpredictable as they were in the unaltered version. The diagnostic signal of an altered pinball "climate" is a highly significant increase in the number of

[8]The pinball machine is a device designed for recreation and amusement that allows the player to shoot steel balls (of roughly 1-in diameter) into an obstacle-strewn field of electronic bumpers that, when struck by the ball, act to increase the net speed of the ball (super elastic rebound). The playing field is slanted so that the ball enters at the highest point. When all five balls have been trapped in the gutter, the game is over. The object of the game is to keep the balls in play as long as possible (through adroit use of flippers near the gutter that propel the ball back uphill and away from the dreaded gutter). The longer the ball is in play, the more it is in contact with bumper collisions that add to the number of points earned. A sufficiently high score wins free replays. Thus, the object of the game is for the player's skill to overcome gravity for as long as possible, somewhat analogous to the efforts of ski jumpers and pole vaulters.

free games awarded. A secondary diagnostic signal, of course, is a noticeable decrease in the received revenues from the machine. It thus is conceptually easy to change the pinball machine's "climate." Detecting changes in pinball machine "climate" and attributing its causes, however, can be easily obscured by the largely random statistics of a fundamentally chaotic system, not unlike in the actual climate.

What do these pinball machine experiments have to do with understanding models of the real climate? Projections for greenhouse warming scenarios depend on a number of physical processes (see above) that are subtle, complex, and not important to weather prediction. However, people outside the climate field are frequently heard to say that climate models are ill posed and irrelevant because they attempt to forecast climate behavior that is well beyond the limits of deterministic predictability and that if one cannot predict weather more than a week in advance, the climate change problem is impossible. Such statements are scientifically incorrect. The "weather prediction" problem is essentially an initial value problem in which the predictability of interesting details (i.e. weather) is fundamentally limited by uncertainty in initial conditions, model errors, and instabilities in the atmosphere itself. In contrast, climate change projections are actually boundary value problems, (e.g. interference with a pinball machine's acceleration of gravity), where the objective is to determine the changes in average conditions (including the average features of the evolution toward the new equilibrium) as the planet is heated or cooled by newly added processes (e.g. increased CO_2).

The differences between weather and climate models are further instructive when one considers how their strengths and weaknesses are evaluated. Thanks to massive amounts of weather and climate data, both kinds of models can be evaluated by careful comparison with data from the real world. In practice, however, the approaches to improving these superficially similar models are very different. The weather models are evaluated by comparing model-based forecasts, started up from real data on a given day, with what happened hours to weeks later. Interestingly, one of the key problems with such weather models is that they can easily reject their initial conditions by drifting toward a model climate that is quite different from that of the real data that was used to start up the detailed forecast calculation. In effect, such a weather forecast model is deficient in the climate that it would produce if released from the constraints of its starting data.

In sharp contrast, a climate model has the responsibility of simulating the time-averaged climate for, say, today's conditions (or for around, say, the year 1800). In this case, the focus of the scientific inquiry is quite different. Here, attention is directed toward proper simulation of the statistics of climate, such as the daily and annual temperature cycles forced by the sun, the number and intensity of extratropical cyclones, locations of deserts and rainy areas, strength and location of jet streams and planetary waves, fidelity of El Niño simulation, location and characteristics of clouds and water vapor, strength and location of ocean currents, magnitude and location of snow accumulation and snow melt, and, finally, amplitudes and patterns of natural variability of all of these on a wide range of timescales (days to centuries).

Achieving all of this in a climate model is a daunting task because the enormous wealth of phenomena in the climate system virtually requires the use of judicious tuning and/or adjustment of various poorly defined processes (such as clouds, or the fluxes of heat between atmosphere and ocean) to improve the model's agreement with observed climate statistics. Such tunings and adjustments are widespread, especially for the global-mean radiative balance, and are often done to ensure that the model agrees with the global-mean features of the climate. If this is not done, a coupled model started up with today's climate will tend to drift toward a less realistic climate. These practices have been criticized as evidence that climate models have no credibility for addressing the greenhouse warming problem. Interestingly, such tunings and adjustments (or lack thereof) may have little to do with the ability of a model to reduce its fundamental uncertainty in predicting anthropogenic climate change. Recall that the key uncertainties highlighted above (water vapor, cloud, and ice albedo feedbacks) revolve around how such properties might change under added greenhouse gases. This is a set of modeling problems that cannot be evaded by judicious model tuning or adjustments. Likely to prove much more fruitful in the long run would be improved fundamental modeling of the key processes that govern the most important climate feedback processes as CO_2 increases (e.g. clouds, water vapor, ice, ocean circulation).

Thus, the models are imperfect tools with which to make such climate-change predictions. Does this mean we should shift our focus to other tools? Definitely not. Statistically based models that use historical data are possible alternatives, but they are of marginal validity, mainly because the recent earth has never experienced the rate of warming expected to result from the current runup of infrared-active greenhouse gases. In this sense, the large, but very slow, global-mean climate excursions of the past geological epochs are instructive, but they are far from definitive as guidelines or analogs for the next century.

The above considerations make it clear that there is no viable alternative to coupled climate models for projecting future climate states and how they might unfold. The physically based climate models have the huge advantage of being fundamentally grounded in known theory as evaluated against all available observations. There are indeed reasons to be skeptical of the ability of such models to make quantitatively accurate projections of the future climate states that will result from various added greenhouse gas scenarios. Fortunately, the weak points of such climate models can be analyzed, evaluated, and improved with properly focused, process-oriented measurements, complemented by well-posed numerical experiments with various formulations of the climate models.[9] In short, the use of such climate models allows a systematic approach to close the gap between theory and observations of the climate system. No alternative approach comes close.

WHY CLIMATE DATA ARE IMPERFECT AND WHY THEY ARE CRUCIAL ANYWAY

The availability of climate data in many forms is crucial in the quest to understand, simulate, and predict the climate system and how it might change in the future. Such data provide the basics for our characterizations of the time-averaged climate states of various statistics of temperature, pressure, wind, water amounts, cloudiness, and precipitation as a function of geographical location, time, and altitude. Most importantly, such data provide invaluable information on the natural variability of climate, ranging from seasons to decades.

These data sets have empowered important direct insights on how the climate system works. For example, the observed average daily and seasonal ranges of mean temperature provide valuable evaluations of our theoretical understanding of how the climate changes in response to changed radiative circumstances (e.g. day to night, summer to winter). On longer timescales, indirect inferences (or proxy measures) provide valuable information on how ice ages and warm epochs appear to depend sensitively on subtle changes to the heating of Earth due to seemingly small variations in the precession of Earth's orientation toward the sun and in Earth's elliptical orbit around the sun. Interestingly, the onset of ice ages and their terminations appear to respond more sensitively to these small solar heating changes than are calculated by our current climate models. For example, the ice core records show that atmospheric CO_2 lowers as the climate cools, a positive feedback effect that we do not expect to be relevant over the next century. However, such observations of prehistoric climates are ambiguous enough that they do not justify any confident conclusions that our current climate models may be underestimating the century-scale global temperature increase due to added greenhouse gases.

[9] Out of many such examples, one of the more interesting is provided by the Department of Energy's Atmospheric Radiation Measurements Program. At a heavily instrumented site in Oklahoma (and at some lesser sites), intensive measurements are made of horizontal wind, vertical velocity, temperature, water vapor, clouds, latent heating, precipitation, short- and long-wave radiative fluxes, and surface fluxes of heat, momentum, and water vapor. This comprehensive set of measurements is being used to evaluate our current modeling capabilities and deficiencies on cloud processes, "cloudy" radiative transfer, convection (thunderstorm scale), and turbulence. These areas represent some of the weakest aspects of the atmospheric parts of climate models.

For the atmosphere, there are thousands of places on earth that collect information daily for the primary purpose of weather forecasting. Fortunately, all the information collected for weather purposes are also central to the needs to characterize longer-term climate. Unfortunately, many kinds of key atmospheric information are not readily available from the weather networks. These include vertical velocity, radiative heating/cooling, cloud characteristics, evaporation, and properties of critical trace species such as particles containing sulfate and carbon.

For the land surface, many local sites provide information on snow, water storage, runoff, and soil moisture. Unfortunately, the spatial coverage is far from adequate, and most stations provide little information on the state of the vegetative cover and its role in governing surface water budgets and reflectivity of solar radiation.

For the world ocean, the data coverage is spotty and episodic relative to the need to characterize the state of the ocean and its role in climate variability and climate change. For example, we are still waiting to see the first instantaneous “weather map” of the internal ocean’s waves, jets, and vortices, a privilege that is taken for granted by atmospheric scientists. Fortunately, the ocean’s surface is partly accessible to measurements from earth-orbiting satellites. This allows remote measurements of ocean surface temperatures, sea state, and ocean height, a measure of integrated density over a fairly deep layer that allows some inferences about ocean currents.

For all parts of the climate system, the ability to characterize long-term trends of key climate variables is minimally adequate at best and nonexistent at worst. Few climate measurement systems currently in place are configured to address what I call the climate monitoring requirement.

Climate monitoring is defined here as the systematic, long-term collection of key climate measurements, with careful attention paid to maintenance of calibration and continuity of records for very long time intervals, and with a strong focus on interpretation of the data gathered. Very few current climate measurement systems satisfy these stringent requirements. This mainly is because of the fact that almost all climate-relevant measurements are gathered for shorter-term purposes such as weather forecasting, and for efforts to understand specific processes such as clouds or El Niño.

So, why should we care about this climate monitoring deficiency? Who actually has a stake in improved climate monitoring? Climate data scientists do because their goal is to use the data to learn about how climate and climate change actually work. Climate theorists and modelers do because the current anthropogenic greenhouse warming projections are theoretically based, as manifested in the mathematical climate models (making climate change projections without attempting to evaluate them against the evolving real world is counter to the ethic of science). Policymakers do because they are already in the process of making policy (or nonpolicy) in the face of an imperfectly understood, but potentially very serious, global environmental threat. Policymakers, like scientists, always need to evaluate their conclusions against new information.

In spite of the compelling needs for improved climate monitoring, not much is now being done nationally or internationally about the current monitoring deficiencies. Even worse, many critical capabilities are deteriorating in the United States and elsewhere because of budgetary pressures. Why is this so? This is a question that continues to baffle me. I suspect the answer lies mainly in the unwillingness of top officials to make firm commitments to a problem that requires sustained focus for many decades.[10] Also, the problem suffers from its apparent lack of glamour. "What? No immediate payoff?" It is also possible that some may not feel much need to get the right answer if their minds are already made up, a phenomenon not unheard of at both ends of the political spectrum.

This summary of some of the barriers to better climate monitoring reveals a serious challenge that is currently producing a net reduction in the global climate monitoring capability at the same time that international policy negotiators are taking the greenhouse warming problem seriously. Clearly, improved information is required to guide the dauntingly tortuous mitigation (or lack thereof) of greenhouse gas emissions over the next century. The emerging climate monitoring information can reveal that our greenhouse warming projections were either too high or too low. Given this information, future mitigation decisions can be strongly affected. Without this key information, we will be flying in the dark much longer.

ROLE OF CONTROVERSY

Context for Controversy

In most of the great political, social, and environmental challenges of our age, controversy and disagreement are key features of the public dialogue. A good rule of thumb is that the intensity of the debate tends to be inversely proportional to the available knowledge on the subject. However, there are spectacular exceptions to this rule of thumb. Consider the pro-life versus pro-choice abortion debate. Here the debates are prolonged and vociferous, even though the science of reproduction and its prevention are rather well understood. Obviously, the continually improving scientific understanding of reproductive science will

[10]It is a personal privilege to acknowledge the pioneering efforts of Charles D Keeling to ensure the presence of today's impressive CO_2 record (this volume). He has taught us that proper climate monitoring is difficult, and invaluable. Perhaps soon the world will begin to take his message seriously.

have little to do with changing the tone of this debate. The abortion debate is about legitimate clashes of value systems that new scientific understanding is unlikely to diminish.

This extreme example provides an instructive context for understanding the character of the intense controversies and disagreements concerning human-caused greenhouse warming. There would not be much of a global warming controversy if increasing greenhouse gases in the atmosphere were perceived to produce an effect of theoretical curiosity—but an effect deemed irrelevant for serious changes in the climate. I can visualize scientists disagreeing, as they typically do, in scientific conferences on points of correct or incorrect explanations of various phenomena. A few might get passionate about their own viewpoint, but the disagreements would not normally prevent the key players from going out later for coffee, beer, or dinner together.

Interestingly, this is a reasonable characterization of what happens at climate conferences, even now. Things change, however, when a member of the scientific community is arguing for a political position "in the name of science." Even in this case, the mood is generally polite, but the questions to the speaker are typically pointed and sometimes emotional. My interpretation is that working climate scientists are not comfortable dealing with the unfamiliar science/nonscience interface. Our instincts are to continue to fight scientifically fair and to openly admit uncertainty, even when unscientific weapons are employed. In effect, serious scientists are trying to find the scientific truth, whereas advocates typically appeal to science to advance their personal agendas. This mismatch often leads to an amplified sense of "scientific" controversy, at least to an uninformed observer.

Genuine Scientific Uncertainty and Disagreement

The above observations are not offered to assert that scientists should not argue. On the contrary, the whole culture of physical science is about disagreements and alternative explanations. But the discipline of science is about settling disagreements using the scientific method. The very ethic of science is designed to get to the truth through hypothesis testing by careful experimentation.

A good test for determining whether or not the scientific method is being used to evaluate assertions about the science of the problem is whether or not previous assertions are altered in the face of contrary evidence. Many instructive examples of legitimate scientific disagreement have energized new understanding in the light of improved information.

The example of the physical explanation of the spectacularly large Antarctic "ozone hole" phenomenon is especially instructive in this context. The new information on the ozone hole discovery changed within about 2 years the way establishment science understood ozone depletion. My own small part in that story was in advancing a testable hypothesis on whether the ozone hole was a natural phenomenon (11). Our hypothesis (the only identified plausible "natural" alternative) was indeed tested and was found to be physically consistent; however, it failed by nearly a factor of 10 as an explanation of the sharp ozone decreases. In real science, if the numbers are off the hypothesis fails. There are self-proclaimed "scientists" who still use terms such as "ozone-hole hoax" to describe the state of ozone science. Clearly, such "scientists" are ignoring compellingly large and convincing ozone decreases, as well as the strong scientific evidence available to explain the decreases.

It is important to recognize that scientific disagreement is a cornerstone of the scientific ethic. Contrary to our legal traditions, all theory, all models, and all data are, in effect, "guilty until proven innocent." Moreover, the proof of innocence in science is inevitably relative. Einstein, in principle, "shot down" Newton's laws of motion. In practice, however, we live our daily lives implicitly assuming the virtual correctness of Newton's laws without fear that the departures from the "true physics" could cause us any observable problems. Thus, we are comfortable with scientific understanding that is "good enough" for application to the purposes at hand.

I suggest that this "good enough" principle provides useful guidance for viewing the human-caused greenhouse warming problem. Obviously, anything as complex and interactive as climate offers plenty of opportunity for legitimate scientific disagreement. My own view is that the climate science community has been straightforward in acknowledging the significant remaining uncertainties in the projections of possible future climate changes. Most importantly, we still acknowledge a factor of three (1.5°–4.5°C) range of uncertainty in the equilibrium global-mean surface temperature response to a doubling of CO_2 (12). In addition, I have asserted that there is a greater than 90% chance that a doubling of CO_2 would produce a warming within that range (13). We scientists acknowledge that adding the effects of sulfate particles (a result of fossil fuel burning) produces an uncertain cooling offset effect. We also freely acknowledge that the aerosol cooling effect was given insufficient attention in the 1990 IPCC Report (14).

These observations strongly indicate that the great controversy about greenhouse warming is not really about the uncertain state of the science. In the scientific community, the uncertainty is widely acknowledged. We do, however, frequently argue about the significance and validity of new claims and new results. The path to sharpened scientific truth is always a rocky one.

The Misuse of Scientific Information

The current, highly energized greenhouse warming debates go well beyond scientific controversy. They are driven by arguments that are not scientific, at least in the sense that practicing scientists use the term. The arguments are frequently, and legitimately, centered around clashes in values and priorities. Unfortunately, however, assertions are being made about climate change "in the name of science" that are not based on fundamental, quantifiable climate science. How is this so? There are many techniques available to use or misuse scientific knowledge to support one's personal viewpoint, which may or may not have much to do with the lessons from the science itself. Actually, it is easy to "mine" the lore of climate facts to justify a particular, preset point of view.

The most obvious misuse of climate knowledge comes from the openly stated uncertainties in the predicted global-mean surface temperature increase for doubled atmospheric CO_2. The widely accepted range of 1.5°–4.5°C leads to some intriguing arguments. Those who are legitimately afraid of the economic consequences of CO_2 mitigation (who I call "Ostriches," with their heads in the sand), almost independent of the scientific evidence, tend to appeal to the information that buttresses the case for the numbers to be at or below the low end of the range. "I just know the real result will be on the low side because...." Those who are legitimately concerned about the environmental consequences of high CO_2 levels (who I call "Chicken Littles," who see the sky falling), almost independent of the scientific evidence, tend to appeal to the information that buttresses the case for the warming numbers to be at or above the high end of the range. "I just know that the real results will be on the high side because...."

Like it or not, the truth is that we do not know the truth about where the final answer will lie. The inconvenient reality is that uncertainty "just is." If we knew that our previous best estimate was, say, on the high side, the scientific community would most assuredly lower the best guess. It would be unscientific to do otherwise. It is clear that well-meaning, but agenda-driven, people will still legitimately disagree for nonscientific reasons. In effect, these are values-driven positions that have little to do with the true state of scientific understanding. People who use such "science" to reinforce their personal opinions are not interpreting science as scientists understand it.

Intriguingly, in the greenhouse warming debates, the natural variability of the climate system is frequently misused in a manner surprisingly analogous to the misuse of scientific uncertainty, as explained above. In this case, Ostriches say that the unforced natural variability of climate is so large that the observed warming trends over the past century are explainable by appeals to the natural variability of, say, global-mean surface air temperature. Thus, for the observed, roughly 0.6°C warming over the past 130 years, Ostriches can properly argue that this might be a natural warming cycle that has nothing to do with the increasing greenhouse gases. However, Chicken Littles can point out that we might have been in a natural cooling cycle over the past 130 years, and thus the greenhouse effect is probably larger than it currently appears from the data. The problem with both these arguments is there is no evidence to confirm either of them. That is one of the reasons it is very difficult to appeal to the temperature record to lower the uncertainty limits on greenhouse warming projections very much. Natural variability, like uncertainty, "just is." No values-driven debating tricks will make this reality disappear. When either uncertainty or natural variability is systematically used to push a prestated position, be wary. Science may just have been misused, to the net loss of a more rational effort to establish what is really going on in the science of this daunting problem.

THE KEY ROLE OF "OFFICIAL" ASSESSMENTS

Over the last two decades there have been roughly a hundred or so published greenhouse warming evaluations and assessments. Almost all have been prepared by single governments or by nongovernmental organizations. Almost all have carried the strong flavor of the perspectives and viewpoints of the entities producing them. Almost all have been virtually ignored on the global scene, apparently because those evaluations were perceived as not credible to entities other than those who wrote them. It was clear that US-based evaluations, including the most recent one (15), were regarded with some mistrust by other countries.

In the ozone-depletion problem, there was a similar history. This pattern was broken, however, with the first truly international ozone assessment (16), sponsored by the World Meteorological Organization. This effort was empowered by a large increase in participation by the world ozone science community and, thus, in the authority of the assessment. An encouraging result was a marked increase in the level of attention and action by the world policy community. In contrast to the current greenhouse warming situation, however, ozone depletion awareness escalated rapidly thereafter, with the 1985 (17) documentation of the Antarctic "ozone hole," a veritable smoking gun that showed the actual problem to be much more severe than had previously been predicted by the ozone science community.

The viability of the greenhouse warming assessment process was strongly improved following the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and its report on *Climate Change: The IPCC Scientific Assessment* in 1990 (14). The IPCC process substantially changed the way the world policy-making and decision-making communities deal with the greenhouse warming issue. The internationalization of the process led to a common platform in which the major contributors to this problem (essentially all human beings) can begin to discuss ways to cope with its implications. In spite of the predictable nit-picking (too aggressive, too timid, too political, insufficiently political), IPCC has proved to be an enormous international success, at least in my opinion.

The IPCC process and its assessment products were far from an instant success. When the 1990 IPCC Report was released, it received a small mention in a back page of the *New York Times*. Almost no other newspapers picked up the story. In effect, it was a nonevent in the US media. Ironically, the impending 1990 IPCC Report had been a very large event in the personal lives of the reporters who were covering the high-amplitude stories that were fueling the greenhouse warming controversy. The reporters had been chasing some assertions that the IPCC report might reach some startling new conclusions. Those of us being interviewed by reporters almost daily before the release of the 1990 IPCC Report experienced a precipitous drop in the frequency of interview requests after the release. My colleagues and I inferred that the IPCC Report was apparently "too dull" to receive major interest from the press. In effect, IPCC was saying what climate scientists had been saying for some time: The greenhouse warming problem is real; human-caused climate change could be substantial; the climate models are credible; and the science has significant uncertainties that must be recognized. I later asked some reporters about this and they acknowledged that our inferences were correct. Without major changes in the public perception of this problem, it was not seen by the reporters as being very newsworthy. In effect, the controversy was much more interesting "news" than the problem itself. The need of the media to find intense and newsy stories had unfortunately overwhelmed whatever obligations it may have had to inform its readers about the significance of the IPCC conclusions.

THE EVOLVING REAL GREENHOUSE WARMING CONTROVERSY

In the months preceding the December 1997 Kyoto Climate Conference, a remarkable shift occurred in the media focus on the greenhouse warming problem. A flurry of articles appeared in the major media that were specifically designed to inform the public about the science underlying greenhouse warming. Suddenly, the science had become newsworthy, and the obligation to educate the public had assumed a much higher priority.

What drove this major shift in media attention toward this long-standing issue? The obvious answer was the Kyoto Conference. This assemblage of representatives of essentially all the nations of the world was charged with beginning the virtually unthinkable—changing the way the world uses fossil fuels to produce its massive energy demands. Suddenly, people all over the planet were involved, and greenhouse warming was no longer a bit player.

Quite literally, the Kyoto process itself was threatening to change everyone's personal world, in possibly large, threatening, and unpredictable ways.

The implications of the Kyoto process led to a flurry of major advertisements and infomercials designed to buttress and/or defend particular points of view. Environmentally oriented persons and groups emphasized the threats that elevated levels of greenhouse gases might cause for life on earth, human and otherwise. Fossil fuel producers and users emphasized potential damage to the economy and to the specific industries that produce and directly use fossil fuels. Both positions were expressing valid concerns.

Fascinatingly, the media jumped back into the greenhouse warming problem at a level that substantially exceeded the level at which they had pursued the original controversies. The media now realized that there are thousands of stories in the upgraded greenhouse story, phase two.

One can understand this dramatic shift in media attention by performing a simple thought experiment. Imagine, by some miracle of scientific wizardry, that the science of greenhouse warming is now definitively complete, that climate scientists can state with amazing precision the ways climate would change under any variety of scenarios of future atmospheric concentrations of greenhouse gases and radiatively active airborne particulates. Would the greenhouse warming controversies go away? Hardly. Indeed, I argue that greenhouse controversies will actually escalate substantially, for a host of readily understandable reasons. Some of the reasons are outlined below.

To illustrate the first reason, assume that the "definitive" state of climate science is being used to evaluate the standard IPCC "toy" scenario of ramping up to a doubling of CO_2 over preindustrial levels and holding it there indefinitely. Also assume that the midrange global-mean estimate for this problem ($\sim 3^{\circ}$C for doubled CO_2) is actually the correct answer. What kinds of specific climate changes might we expect to see? According to Manabe & Stouffer (19) and IPCC (12), we would expect (*a*) land to warm more than oceans, (*b*) a substantial retreat of northern hemisphere sea ice, (*c*) sea level to rise more than a meter over the next several hundred years, (*d*) a sharp reduction in the overturning circulation of the North Atlantic ocean, and (*e*) substantial reductions in midcontinental summer soil moisture ($\sim$25%). Also, we would expect increases in the intensity of tropical hurricanes/typhoons, at least for those that tend to reach mature stages (20). Sharp increases in summertime heat index (a measure of the effective temperature level a body feels on a humid day) would be likely in moist subtropical areas (21). The above list of changes, if realized, would place significant stresses on many aspects of life on earth. It is likely there would be many losers and some winners. The values and equity clashes resulting from this kind of a human-caused climate change scene are likely to be intense and long lasting.

For the second reason to expect amplified controversy, note that there remains an important possibility that the actual climate sensitivity could be near the lower limit of the generous ranges of the current best estimates ($\sim$1.5°C for doubled CO_2). Even this lower level of climate sensitivity to added CO_2 can become problematic, however. As pointed out in the 1994 IPCC Report on *Radiative Forcing of Climate Change* (18), our current fossil fuel–use social trajectory is pointing well toward a quadrupling of CO_2 levels over their preindustrial values. At those high CO_2 levels, even this lower level of warming response to CO_2 increases, and its potential impacts become surprisingly "unsmall" (see the doubled CO_2 effects for the midrange estimate above).

A third reason is that, near the current upper limits of climate sensitivity for the current societal CO_2 trajectory, the large projected climate changes indicate that the potential impacts would likely become dauntingly large (19).

The above hypothetical cases point out that there almost inevitably will be a growing global requirement to move toward a change in the world's use of fossil fuels. That, of course, is what the Kyoto Conference was all about—to begin the process of nudging the world away from its current fossil fuel usage profile in the interest of preventing substantial climate change.

The Kyoto process was widely criticized for doing too much, for doing too little, or for being too lenient on the CO_2 emissions being produced by the other guy (country, industry, generation...). Obviously, this "Who pays and how much and when?" debate is already the source of major controversy that is guaranteed to escalate as these "agreements" evolve toward real commitments by real countries, real industries, and real individuals. Now the real controversies begin. Now values clashes become substantive, and ubiquitous. Most of us want to ensure that our particular set of wants and needs are not disproportionally impacted. Equity-driven values debates will inevitably be contentious and emotional. We thus are left with the conclusion that Kyoto's real purpose was to initiate the effort to nudge us down from our current social trajectory that is pointing toward quadrupled CO_2 levels (18). The really hard decisions will have to be made in a future series of "Kyoto" conferences.

Beyond the Kyoto process, the controversies are almost guaranteed to escalate further. Underlying the Kyoto approach is what appears to me to be an implicit assumption: We can proceed reasonably on the policy side if we can all quietly assume, for now at least, that an eventual doubling of CO_2 levels would lead to an acceptable level of climate change, but that higher CO_2 levels would become progressively problematic. From the current scientific information base, what major entities have concluded that? Certainly not the IPCC 1995 assessment (12). The uncomfortable answer is that no major bodies have reached such a conclusion. So what is going on? I suspect that this implicit assumption is actually driven by the widely, but not unanimously, perceived enormous difficulty in capping the eventual CO_2 at a doubling, let alone at lower levels. The Kyoto process seems to have quietly and wisely concluded that it needed to begin from some point that allows incremental actions to begin, even if they are small steps relative to the real problem.

Thus, the REAL greenhouse warming controversy is almost guaranteed to escalate further. In order for the Kyoto process to have had any rational hope of success, the other half of this effort had to be left off the table. Other half? Well, yes. The Kyoto debates were about who pays for the initial costs of reducing CO_2 emissions. The part left undiscussed was the debate about who "pays" for the impacts caused by the unmitigated CO_2 emissions. The tacit agreement to allow significant climate change (CO_2 doubling or more) was "left home" in the Kyoto process. This highlights another fundamental values debate that will surely add daunting levels of complexity and emotion to the process. The equity issues are multidimensional: climate change winners versus losers; rich versus poor; environment versus economy; our generations versus future generations... In short, the values, equity, and impacts debates on the cost of realized climate change will inevitably be addressed in a substantially more focused way than is currently underway. The stakes and the emotional levels of the arguments will be very high. There will likely be clear winners and clear losers. It will take a long time, decades to a century, to sort all this out. This is because the costs of sufficiently aggressive mitigative action are likely to be very high, clearly so if net global CO_2 emissions are to be sharply reduced. However, the "costs" of doing too little to prevent significant climate warming are also likely to be very high and would be levied for many centuries.

Simply put, this problem has no soft landing spot. This is the REAL greenhouse warming controversy. Think of it as our "present" to our great grandchildren.

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Literature Cited

1. Arrhenius S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *London Edinburgh Dublin Philos. Mag. J. Sci.* 41:237–76
2. Manabe S, Wetherald RT. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.* 24:241–59
3. Lindzen RS. 1990. Some coolness concerning global warming. *Bull. Am. Meteorolog. Soc.* 71:288–99
4. Oort AH, Liu H. 1993. Upper air temperature trends over the globe. *J. Clim.* 6:292–307
5. Sun D-Z, Held IM. 1996. A comparison of modeled and observed relationships between interannual variations of water vapor and temperature. *J. Clim.* 9:665–75
6. Phillilps NA. 1956. The general circulation of the atmosphere: a numerical experiment. *Q. J. R. Meteorolog. Soc.* 82:123–64
7. Smagorinsky J. 1963. General circulation experiments with the primitive equations. I. The basic experiment. *Mon. Weather Rev.* 41:99–164
8. Smagorinsky J, Manabe S, Holloway JL Jr. 1965. Numerical results from a nine-level general circulation model of the atmosphere. *Mon. Weather Rev.* 43:727–68
9. Lorenz EM. 1963. Deterministic nonperiodic flow. *J. Atmos. Sci.* 20:130–41
10. Cane M, Zebiak SE, Dolan SC. 1986. Experimental forecast of El Niño. *Nature* 321:827–32
11. Mahlman JD, Fels SB. 1986. Antarctic ozone decreases: a dynamical cause? *Geophys. Res. Lett.* 13:1316–19
12. Houghton JT, Meira Filko LG, Callender BA, Harris N, Kathenberg A, Mackell K, eds. 1995. *Climate Change 1995: The Science of Climate Change*. Cambridge, UK: Cambridge Univ. Press. 572 pp.
13. Mahlman JD. 1997. Uncertainties in projections of human-caused climate warming. *Science* 278:1416–17
14. Houghton JT, Jenkins GJ, Ephraums JJ, eds. 1990. *Climate Change: The IPCC Scientific Assessment. Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press. 364 pp.
15. Evans DJ. 1992. *Policy Implications of Greenhouse Warming*. Washington, DC: Natl. Acad. 918 pp.
16. World Meteorological Organization. 1985. *Atmospheric Ozone 1985, Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change*. World Meteorolog. Org., Global Ozone Res. Monitoring Proj. Rep. 16. 478 pp.
17. Farman JC, Gardiner BG, Shanklin JD. 1985. Large losses of total ozone in Antarctica reveal seasonal $Cl0_x/NO_x$ interaction. *Nature* 315:207–10
18. Houghton JT, Meira Filko LG, Bruce J, Lee H, Callander BA, et al, eds. 1994. *Climate Change 1994: Radiative Forcing of Climate Change. Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press. 339 pp.
19. Manabe S, Stouffer R. 1994. Multiple-century response of a coupled ocean-atmosphere model and increase of atmospheric carbon dioxide. *J. Clim.* 7:5–23
20. Knutson TR, Tuleya RE, Kurihara Y. 1998. Simulated increase of hurricane intensities in a CO_2-warmed climate. *Science* 279: 1018–20
21. Delworth TL, Mahlman JD, Knutson TR. 1998. Changes in heat index associated with CO_2-induced global warming. *Clim. Change.* In press