Experimenting with Earth

by V. Ramanathan and Tim P. Barnett

In 1827, the French physicist Jean Baptiste Joseph Fourier made a remarkably prescient assertion: "The question of global temperatures, one of the most important and most difficult in all natural philosophy, is composed of rather diverse elements that should be considered under one general viewpoint." Nearly 200 years later, climate scientists are still trying to develop this "general viewpoint." We now recognize that the problem is every bit as complicated and formidable as Fourier presumed—and perhaps even more important. Global temperatures are regulated not just by chemical, physical, and dynamical processes (the latter comprising convection and large-scale circulation) but by human and other biological processes as well. Fueled by growing scientific concern that human activities may significantly alter the world's climate—if they have not already done so—major national and international efforts have been launched to explore and analyze the diverse elements of the climate system.

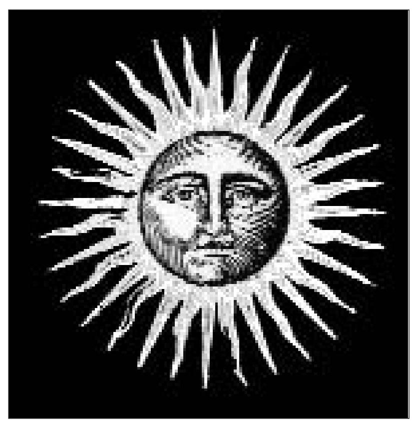
The fundamental energy source for Earth's climate system is solar energy. The planet absorbs only about 70 percent of the incoming solar energy and, in turn, emits infrared energy into space to offset the solar heating. Over the long term, climate is governed by the balance between the incoming solar heating and the cooling associated with the outgoing infrared energy.

Atmospheric gases, such as water vapor and carbon dioxide, absorb infrared energy emitted by the planet's surface that would otherwise escape into space. These gases also emit infrared energy into space, but because the surface of the planet is, on average, much warmer than the atmosphere, the eventual result is a net trapping of infrared energy within the atmosphere. (Atmospheric gases absorb some incoming solar radiation as well, but this has only a negligible impact.) This reduction of the outgoing infrared energy by atmospheric gases is what we call the *greenhouse effect*.

Water vapor, carbon dioxide, and clouds are the major contributors to the natural atmospheric greenhouse effect, with water vapor the dominant greenhouse gas. (Some of the major gaseous constituents of the atmosphere, such as nitrogen and oxygen, do not contribute to the greenhouse effect.) Advances in atmospheric gas sampling have revealed a significant increase all over the globe in the concentrations of several atmospheric gases—especially carbon dioxide, methane, chlorofluorocarbons (CFCs) and other halocarbons used as refriger-

ants and propellants, nitrous oxide from fertilizers, and lower-atmosphere ozone. For a long time, the prevailing view with respect to anthropogenic (human-generated) sources was that carbon dioxide was the only one of concern. The importance of the dozens of other greenhouse gases (including CFCs, methane, and ozone) was not recognized until the mid-1970s, when it was found that one molecule of CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) can have the same greenhouse effect as 10,000 molecules of carbon dioxide. The CFCs and other anthropogenic greenhouse gases besides carbon dioxide currently contribute about 40 percent of the total anthropogenic greenhouse effect.

The observed increases in greenhouse gases have added infrared energy equal to about 2.5 watts per square meter (Wm^{-2}) of Earth's surface to the planet since the 1850s. That's equivalent to increasing the energy from the Sun by one percent. To put it another way, it's equivalent to burning one 250-watt electric light bulb for every 100 square meters of Earth's surface continuously every second of the day throughout the year. How does the planet deal with this sudden (in terms of geologic time) excess of energy, which it must somehow get rid of to maintain a stable climate?



Let's conduct a thought experiment. Consider the planet before humans started adding greenhouse gases in substantial quantities. It was in equilibrium, with the absorbed solar radiation balancing the infrared energy exiting into space. Enter James Watt, who ushered in the industrial era with his invention of the modern steam engine in 1784. Nobel Prize-winning chemist Paul Crutzen has argued that this development jolted Earth into a new geological era he calls the *Anthropocene*, with human beings profoundly influencing the environment. Greenhouse gases begin to accumulate in the atmosphere, and, as a consequence, more infrared energy is trapped and the amount of infrared leaving the planet to balance the solar heating is reduced. (However, because scientists lack suitable measurements from space, this reduction has not been confirmed.) Earth warms until the excess infrared energy is finally radiated into space to reach a new equilibrium that is warmer than the preindustrial climate. *In sum, the warming of the planet in response to a buildup of greenhouse gases is indisputable; it's based on fundamental and well-tested laws of thermodynamics and physics.*

The important practical issue concerns the magnitude of the warming. How great is it? In answering this question, one must combine the deductions from fundamental physics and thermodynamics that we've discussed with results from climate-modeling efforts. Although we still have a long way to go in developing the models, they have improved a great deal in the past decade.

Feedback effects are one of the greatest imponderables in these models. The ultimate source of water vapor in the atmosphere is evaporation from the oceans. More moisture will evaporate from a warmer ocean. Basic water vapor

thermodynamics dictates that the amount of moisture the atmosphere can hold increases exponentially with temperature. (This explains why winters outside the Tropics tend to be dry and summers humid—the colder winter air simply can't hold as much moisture as the warm summer air.) As a result, the greenhouse warming of the atmosphere increases the amount of water vapor, which, in turn, can further amplify the warming. A conceptually simple model incorporating these deductions has been built, and it, along with many of its variants, suggests that the increase in greenhouse gases since the 1850s should have committed the planet to a warming of about 1°C. (Without the positive water vapor feedback, the estimated warming would be smaller by about 30 to 50 percent.)

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However, because of the strong links among the atmosphere, the cryosphere (ice and snow), the oceans, and the land, the predicted warming is not uniform, but varies significantly with latitude, longitude, altitude, and season. The temperature and pressure gradients that result from the non-uniform warming patterns can alter the general circulation of the atmosphere and the oceans and perturb the variables that depend on the circulation—namely, clouds, water vapor, ice sheets, and vegetation. These changes exert a feedback effect on global warming because they influence the absorbed solar and outgoing infrared energy.

To sort out these feedbacks, we must turn to more sophisticated climate models than the one with which we began. The most advanced and detailed four-dimensional global climate models (incorporating altitude, latitude, longitude, and time) suggest that the committed warming should have been between 1.5°C and 2°C, instead of the 1°C warming we estimated earlier. Feedbacks among the warming, ice and snow cover, and clouds lead to the amplification.

It's important to recognize that the extent of global warming is not fully and immediately reflected in Earth's surface temperatures. Because of the "thermal inertia effect" of the oceans and their large heat capacity, a lot of heat is stored in the depths of the oceans. Through a process of convective overturning, the oceans transport infrared energy to their deeper layers. Basically, the oceans sequester the additional heat, delaying the full impact of greenhouse warming. Only much later will the heat stored in the ocean depths warm the oceans and the atmosphere. "Later" could mean anything from a few decades to a few centuries. Thus, the *realized* warming will always be smaller than the *committed* warming. Our best understand-

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ing of climate feedbacks and the rate at which heat is stored in the oceans suggests that the realized warming during the 20th century should have been about 50 percent to 75 percent of the committed warming.

To see how well all of these deductions and model predictions square with reality, we can compare them with real-world observations.

a. Taking into account the thermal inertia of the oceans, the realized warming we should have observed from 1850 to 2000 is about 0.5°C to 1.5°C. (These figures refer to the global average of surface temperatures, over land and sea.) The 0.5°C is based on the simple model's result of 1°C committed warming and a 50 percent value for the realized warming. The 1.5°C warming is obtained by using the upper range of value for the more sophisticated model's estimate and the upper range of 75 percent for the realized warming.

In fact, global surface temperature records reveal a warming trend of about 0.6°C (give or take 0.15°) between 1850 and 2000. That's certainly within the range predicted by the models, though it's less than half of what the more sophisticated model predicts. Some or most of this discrepancy can be accounted for by the cooling effect of sulfate particles of anthropogenic origin (which we'll describe later). In addition, natural causes contributed to the observed climate changes during this period.

About half of the observed warming occurred between 1900 and 1940. After that period, the global mean temperature went into a cooling trend until the mid-1960s, followed by a larger warming trend that has continued to the present day. Warming induced by greenhouse gases cannot, by itself, explain these swings. Natural variations in the energy output of the Sun, cooling due to the scattering of solar energy back to space by sulfate aerosols from volcanic eruptions (in addition to sulfates from anthropogenic emissions), and nonlinear climate dynamics account for some of the warming trend until the 1940s and the cooling trend from the 1940s to mid-1960s. But none of these other factors can account for the large warming trend of the latter part of the 20th century. At least a half-dozen global climate model studies show, to a high degree of statistical certainty, that greenhouse gases are the dominant contributor to this warming.

b. Because some of the excess infrared energy is stored in the oceans, the amount of heat stored in the oceans should be increasing with time.

Records of ocean temperatures down to a depth of about 3,000 meters stretch back to the 1950s. A recent study demonstrates that the heat content of all the world's oceans has increased steadily during the past 50 years. The rate of increase matches very closely, with a high degree of statistical significance, the model-simulated increase attributable to greenhouse gases.

c. The water vapor content of the lower atmosphere should be increasing with time.

The vertical distribution of water vapor is gauged by humidity-measuring instruments flown on balloons, but the measurements are few and far between. Nevertheless, available records do show that the amount of water vapor in the lower atmosphere (up to five kilometers from Earth's surface) has increased during the past 50 years.

d. The warming should be greater at higher latitudes because the brighter ice and snow reflect more radiation.

This is also happening. Alaska, for example, is experiencing a significant warming, along with ecosystem changes.

e. The snow cover on land, especially glaciers, and the sea ice cover should be retreating toward the poles.

It's been shown that arctic sea ice has thinned by about 45 percent over the past 30 years, and landlocked glaciers such as those in the Himalayas are in retreat in most parts of the globe. If the warming continues, it's estimated that the Asian glacier field, the third largest collection of ice on the planet after the Antarctic and Greenland icecaps, will vanish during this century.

In short, there's compelling evidence to conclude that the observed warming over the past 50 years is attributable largely to anthropogenic increases in greenhouse gases.

Jack Hollander's main reason, in his essay elsewhere in this issue, for skepticism about the role of anthropogenic greenhouse gases in global warming is the 20-year record (1979–98) of satellite-based estimates of atmospheric temperature change. As he points out, these estimates seem to show that Earth's atmosphere has not warmed very much, or may even have cooled slightly, while the surface has warmed. If that's true, it's a major setback for the particular climate models we now have—though not necessarily for predictions of global warming. Two independent groups have examined the same satellite data, and they've come to conflicting conclusions. Hollander relies on an analysis by John Christy and his colleagues in 2000. An analysis by Frank Wentz and several colleagues in 2002, using exactly the same data employed in the Christy study, reveals a warming of the atmosphere in closer agreement with greenhouse models.*

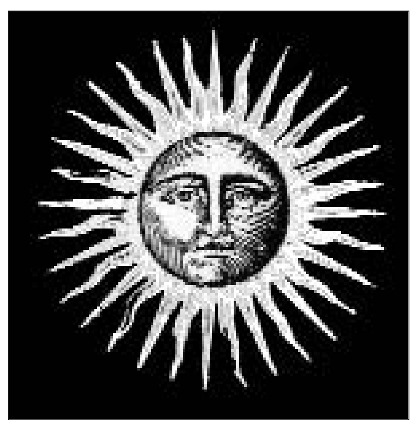
By the beginning of the next century, the global population is expected to reach about nine billion, and many people in the developing world will be striving to match Western standards of living. Their efforts will entail enormous additions of atmospheric pollutants, alterations of the landscape, and other environmental stresses. Atmospheric carbon dioxide is expected to double, at least, from its preindustrial value of 280 parts per million by the next century. The infrared energy added to the planet by greenhouse gases will amount to at least 4 Wm^{-2}. According to our best understanding of the system, that could warm the planet by another 1.5 to 4.5°C (3 to 8°F), depending on the competing effects of aerosols in the atmosphere and the feedback effects of clouds and the cryosphere. But averages don't tell the whole story: The regional changes and impacts are expect-

*The fact that two reputable studies can produce such a disagreement should not be surprising. The temperatures they report are not obtained directly from thermometers but indirectly through devices called microwave sounder units that operate from polar-orbiting satellites. To derive temperature figures from the data these devices provide, researchers must run the data through computer models, a process that introduces several large degrees of uncertainty. In addition, the instruments were not designed to estimate temperature trends on the order of what's being examined—a tenth of a degree per decade.

ed to be much larger than global mean changes. The atmosphere and the planet, it would seem, are headed toward uncharted territory.

Uncertainties surround any attempt to predict climate changes. Changes in clouds, for example, have effects on climate change that are very difficult to measure. For decades, models predicted that clouds would be shown to have a net cooling effect, and those predictions were confirmed in 1989 by data from the Earth Radiation Budget Satellite Experiment, a project of the National Aeronautics and Space Administration. The data reveal that solar radiation reflected by clouds exceeds the infrared greenhouse effect by a significant 15 to 20 Wm^{-2}. In other words, clouds have a cooling effect about five times larger than the warming effect from a doubling of carbon dioxide. The great unknown, however, is what will happen in the future, after all possible feedbacks are considered, if cloudiness increases or decreases. It's possible that cloudiness could lessen future warming—and possible, too, that it could increase warming.

Another uncertainty has been introduced by human activities, such as the release of sulfur dioxide from coal combustion, that have altered the sulfur cycle. Anthropogenic emissions of sulfur dioxide, which converts into sulfate particles in the atmosphere, exceed those from natural sources, such as volcanic emissions, by more than a factor of two. Sulfate particles exert a cooling effect in two ways: directly, by scattering incoming sunlight back into space, and indirectly, by nucleating more cloud drops and increasing the brightness of clouds. These direct and indirect effects may have counteracted as much as 30 to 75 percent of the greenhouse warming the planet might otherwise have experienced.



Carbonaceous aerosols created by fossil fuel combustion and biomass burning have become another major source of particles. They're an ingredient in the complex chemical soup called "brown cloud" now seen in Los Angeles and many other urban regions around the world. Brown cloud is not just a phenomenon of cities; it can span an entire continent or ocean basin. A disturbing example is the so-called Asian brown cloud, a blanket of aerosols, ash, soot, and other particulates, perhaps two miles thick, that is concentrated over much of southern and eastern Asia.

Aerosols have a much larger effect on the regional radiative heating of the planet than greenhouse gases do. They cause a large reduction in the amount of sunlight reaching Earth's surface, a corresponding increase in solar heating of the atmosphere, changes in atmospheric temperature structure, suppression of rainfall, and less efficient removal of pollutants. These aerosol effects can lead to a weaker hydrologic cycle and global drying, outcomes that can compete with the effects of global

warming on precipitation. Researchers have linked sulfate aerosols and the brown clouds to droughts in recent decades in the Sahara, eastern China, and southwest Asia.

The key issue with respect to clouds and aerosols is the extent to which the solar radiation reflected by the planet is out of equilbrium with its pre-Anthropocene values. Accurate radiation-budget measurements from space were begun only in the 1980s, and we need to continue them to document this major human impact.

In spite of the complexities surrounding it, global warming caused by greenhouse gases will be the most important environmental challenge facing the world during the 21st century, and possibly the 22nd century as well. There's a simple reason for this: The greenhouse gases we're now adding to the atmosphere have very long lifetimes—on the order of centuries. (Aerosols, in contrast, survive only for weeks.) Put in simple terms, about 10 to 30 percent of the carbon dioxide we release from our cars today will still be circling the globe 100 years from now, contributing to conditions on the planet our great-grandchildren will inhabit.

For every decade that passes without action to cut the emission rate of greenhouse gases, we're committing the planet to an additional warming of about 0.1 to 0.2°C. In effect, we're making the next generation's climate now, and there will be nothing they can do about it! Or worse still, the next generation may be forced to resort to engineering the climate *advertently* to offset the *inadvertent* changes caused by greenhouse gases.

The time to act is now. It's particularly important to recognize that the use of global averages in discussions of global warming's impact masks much more marked changes that are likely to be seen at the regional level. These localized changes can produce a vast number of major practical problems. In the western United States, for example, winter snow is likely to melt earlier than in the past, posing new difficulties for those attempting to manage the West's scarce water resources. (On the whole, it should be noted, poorer nations will probably suffer the most from climate change.)

The experienced climate scientist concerned today about global warming is like a ship's engineer who hears disturbing noises in the boiler room and warns the captain of impending danger. But the captain, determined to make port on schedule, pays no attention, insisting on absolute proof. The planet is undoubtedly making disturbing noises: To the list we've already enumerated we would add worldwide changes in biota (coral reefs, pests, and disease vectors) and glacier surges following the collapse of ice shelves on the Antarctic Peninsula and rising sea levels. Our observational records and models are far from perfect, and it may take decades to make them sufficiently conclusive to convince everyone. By then the deed will have been done. As we continue to ignore or debate the issue, the question we must ask ourselves grows ever more urgent: How much risk do we want to take before slowing down the experiment human beings are performing on the planet? ❑