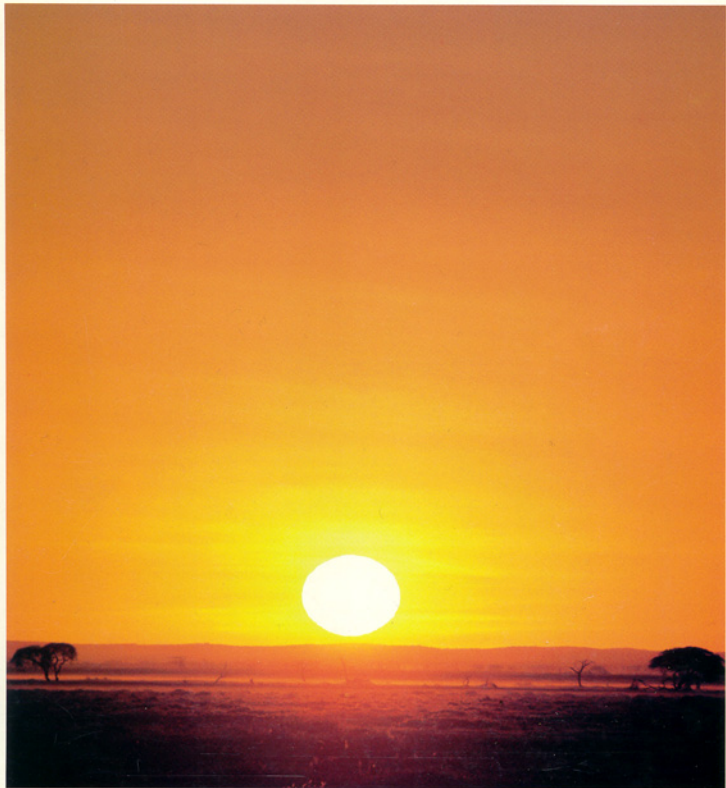


ORION

\$4

NATURE QUARTERLY



Published by the Myrin Institute in association with Conservation International • Winter 1989



**IN SEARCH OF
THE GREENHOUSE
FINGERPRINT**

by William R. Moomaw

The greenhouse effect may seem to have sprung full-blown into the public consciousness in a remarkably short time. In fact, the notion first appeared in print over 160 years ago and has been forgotten and rediscovered by the scientific community at least four times. Thus, in addition to its significance as the most far-reaching environmental and societal issue we have yet faced, the greenhouse effect provides a fascinating example of how science constantly refines itself through the interplay of theoretical ideas, observations, and continual testing for consistency.

Questions and speculations about the origin and age of the earth and its myriad species were well developed by the first quarter of the nineteenth century, even though the scientific knowledge needed to address these issues was largely unavailable. Climatology perhaps began when physicists became intrigued with the question of how the earth managed to maintain its relatively warm temperature. It was the great French mathematical physicist Jean Fourier (d. 1830) who argued that the atmosphere acted like the glass of a greenhouse by letting in the visible rays and energy of the sun, but impeded the radiation of heat from the warm earth back into cold outer space. Fourier missed the point that glass helps greenhouses stay warm mostly by keeping the warm, solar-heated air within from mixing with the cooler air outdoors, rather than by trapping radiant heat. Nevertheless, the misnomer has persisted, and planetary warming by greenhouse absorption of radiant heat is still commonly referred to as the greenhouse effect.

The realization that the bulk of the atmosphere, 99 percent of which consists of nitrogen and oxygen, absorbed none of the sun's rays nor the earth's radiant heat was difficult to reconcile with Fourier's notion. It was found, however, that the job of absorbing radiant heat, or infrared radiation, as it came to be known, rested with trace amounts of atmospheric water vapor and carbon dioxide. In 1896, the productive

Swedish chemist Svante Arrhenius took the newly acquired data on the infrared-absorbing properties of these two substances and combined them with the American Samuel P. Langley's measurement of solar intensity to produce the first good quantitative calculation of atmospheric warming. He correctly concluded that although their presence was minute, water and carbon dioxide molecules together absorbed enough infrared radiation to warm the earth by nearly sixty degrees Fahrenheit. Instead of being an ice-bound, frozen planet, the earth had a climate amenable to the carbon-based biochemistry that has given rise to approximately ten million living species.

Not satisfied with establishing the correctness of this important insight, Arrhenius went on in his paper to address the question of what would happen if industrial societies continued to add carbon dioxide to the atmosphere through the burning of fossil fuels such as coal, oil, natural gas, and peat. After a rather detailed analysis, Arrhenius concluded that a doubling of atmospheric carbon dioxide would raise the average global temperature by an additional ten degrees F. (he later revised this to seven degrees). His calculations come very close to the best current estimate of three to eight degrees F., which is based upon better data and more elaborate analysis. In other words, Arrhenius correctly deduced that increasing the amount of carbon dioxide in the atmosphere can turn the greenhouse into a "heat trap," as Norway's Prime Minister, Ms. Gro Harlem Brundtland, recently termed this overheating.

After Arrhenius, little additional discussion of the greenhouse issue appears to have taken place until a British engineer, G.D. Gallendar, in 1938 carried out the first direct comparison between the measured growth of carbon dioxide in the atmosphere and long-term temperature records from 200 meteorological stations. Using improved data, he updated Arrhenius's calculation and showed that his estimated temperature rise of 0.5 degrees F per century was in



*Gro Harlem Brundtland,
Prime Minister of Norway.*



*Roger R.D. Revelle,
Scripps Institution of
Oceanography.*



*Charles David Keeling,
Scripps Institution of
Oceanography.*



*George M. Woodwell,
Director, Woods Hole
Research Center.*



*Verahadran
Ramanathan, University
of Chicago.*

close agreement with the measured value of 0.9 degrees F. per century. The response to Callendar's paper following its presentation to the British Royal Society was highly skeptical of the proposed link between increased atmospheric carbon dioxide and global warming. Callendar was undaunted and moreover was optimistic that the added carbon dioxide was "likely to prove beneficial to mankind in several ways," as increased "mean temperature would be important at the northern margin of cultivation." He also felt that plant growth would improve with increased carbon dioxide in the atmosphere, and "in any case the return of the deadly glaciers should be delayed indefinitely."

Although sporadic measurements of atmospheric carbon dioxide had been made 1870, it was not until 1958 that anyone began to develop a continuous record to measure just how fast it was accumulating. Roger Revelle of the Scripps Institution of Oceanography in California teamed up with a young chemist, Charles David Keeling, to measure carbon dioxide at a remote site far from human activity in order to determine what changes were occurring in the uncontaminated atmosphere. Keeling's continuous, thirty-year record of carbon dioxide at the Mauna Loa Observatory in Hawaii is one of the most striking sets of natural data ever gathered.

Figure 1 displays the remarkable interplay between ecology and economics revealed in the carbon dioxide record. The annual oscillations reflect the processes of gas exchange of the entire northern hemisphere. During spring and summer, green plants convert more carbon dioxide into sugars and cellulose than they require for their own metabolism, and atmospheric levels of carbon dioxide decrease. During fall and winter, when many trees lose their leaves, more carbon dioxide is released than is incorporated into plants, and atmospheric levels increase. That is the ecological side of the story. Superimposed upon these annual oscillations is an inexorable rise in carbon dioxide levels that reflects the activity of human societies. The burning of fossil fuels is responsible for most of the carbon entering the atmosphere, some 5.9 billion tons each year, or one ton for each person living on the planet. During the past two decades, George Woodwell at the Woods Hole Research Center has established that deforestation, especially in the tropics, is the other major contributor of carbon dioxide to the atmosphere, adding approximately

one-fifth to the annual increase.

Extrapolating these data backward, it is estimated that we have seen a 25 percent increase in atmospheric carbon dioxide since the beginning of the Industrial Revolution, around 1800. Because of the accelerating rate of fossil fuel use and deforestation, just over half of this increase has occurred in the thirty years since Keeling began his measurements in 1958. If current trends continue, with atmospheric carbon dioxide increasing by 0.4 to 0.5 percent per year, pre-industrial levels will have doubled before 2075.

During the 1970s, attention was focused on atmospheric problems such as urban air pollution and the depletion of the stratospheric ozone layer that seemed unrelated to global warming. It was only a decade later that their significance for the greenhouse effect would be fully recognized. An atmospheric scientist at the University of Chicago, Verahadran Ramanathan, first pointed out in the mid-1970s that the chlorofluorocarbons (CFCs), confirmed as stratospheric ozone depleters, shared with carbon dioxide the radiant-heat-absorption properties that cause global warming. His initial claim went largely unnoticed because the concentration of carbon dioxide was five hundred thousand times greater than that of CFCs; it was thought that CFCs would have only a negligible effect on global warming. Over the next ten years, Ramanathan and Ralph Cicerone of the National Center for Atmospheric Research at Boulder, Colorado, showed that each CFC molecule produced a warming effect roughly ten thousand times that of an added molecule of carbon dioxide. Moreover, measurements revealed that the additions of these commercial chemicals to the atmosphere were increasing at ten times the carbon dioxide growth rate. These researchers further demonstrated that methane, nitrous oxide, and oxidants such as ozone formed in the photochemical smog of urban air pollution were also greenhouse gases that were accumulating rapidly in the atmosphere.

Their findings have startling implications. These additional gases now contribute as much to global warming as does carbon dioxide, and will soon surpass it in heating effect. Projecting into the future, the combination of growth in all of the greenhouse gases means that the warming predicted to result from a doubling of carbon dioxide alone in 2075 will occur as early as 2030. This is well within the lifetime of many people living today.

But has the earth warmed? In some locations, temperatures have been recorded continually for over 100 years. Two research groups, one in England under Thomas Wigley and a second in the United States under James Hansen at NASA, have analyzed millions of individual measurements from all over the

globe. They have had to exercise great care, since not all data are equally reliable, and higher urban temperatures must be corrected for the local heat islands created by the concentrated release of energy from cars and buildings. After carefully evaluating all such factors, both groups independently concluded that

Atmospheric CO₂ Variations 1958–1986

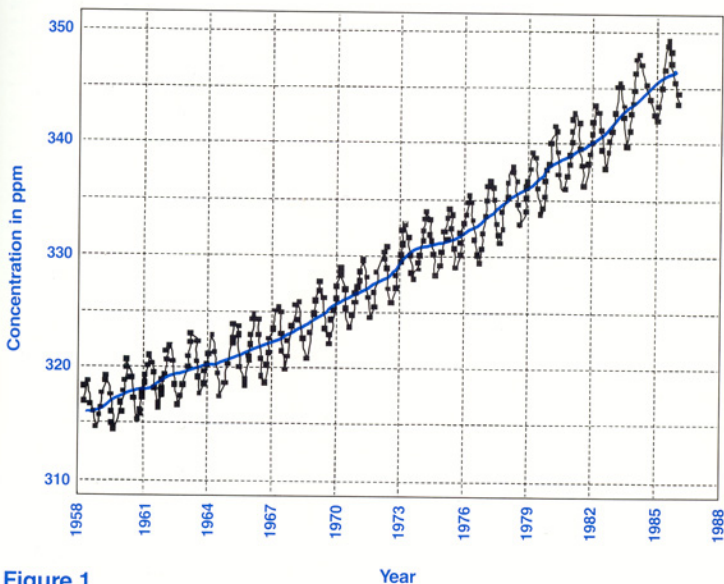


Figure 1

Year

Global Temperature Trend

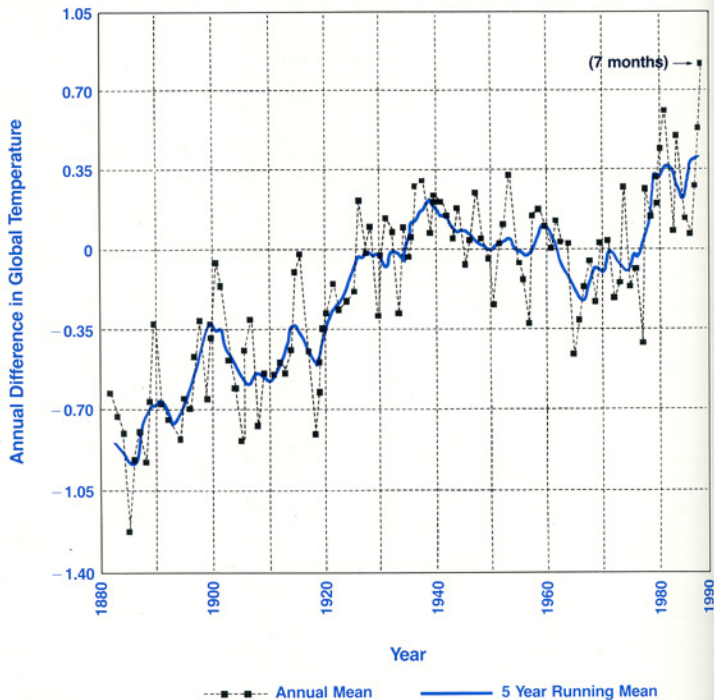


Figure 2

there has been a rise of about one degree Fahrenheit during the past century, and that nearly half of that rise has occurred since 1965 (see Figure 2). Hansen caused a major stir in June of 1988 when he testified before Congress that, based upon a statistical analysis of the data, there was a 99 percent certainty that the recent increases lay outside the range of normal temperature fluctuations. In other words, the earth's climate, which is defined as the thirty-year average of temperature (and weather), may be changing.

At this point it is important to ask a question: is the observed temperature rise caused by the buildup of greenhouse gases? The answer is a resounding "maybe." It is enormously difficult to prove cause and effect, especially when they are separated in time and linked by a complex set of interactions. It is even more difficult to convince policymakers and the public of the connection, when many of the measurements and the theory linking them are known only to a relatively small group of scientists. Just remember how hard it was to convince governments and industry that the benign chemicals (CFCs) used to operate our refrigerators and air conditioners, to provide us with insulation and foam for our mattresses and chairs, and to keep our computers and communications systems functioning, were the cause of ozone loss in the stratosphere. Researchers assembled many pieces of evidence over more than a decade to persuade governments that a problem existed, and it required the discovery of the Antarctic ozone hole to capture the attention of the world. We cannot afford to wait for a similar event to dramatize the danger of greenhouse gases. By the time the greenhouse effect is noticeable to the person on the street, we will have committed ourselves to substantial additional warming that will take many decades to reverse.

What is clearly needed is a greenhouse early warning system. To develop such a system we must determine what additional consequences can be expected to arise from global warming. We could then search for a pattern of such events, which would define a kind of "greenhouse warming fingerprint." We must build a plausible case based upon a collection of factors, no one of which may be convincing by itself, but which taken together provide a framework for judging whether or not our atmosphere has become a heat trap.

Two principal elements are already in place. The first is the direct observation of an increase in green-

house gases, and the second is the measured rise in temperature by about the amount predicted by theory. We know, however, that there is uncertainty in the earlier temperature measurements, and no one has a complete explanation for the leveling and slight decline in temperatures that occurred between 1940 and 1965. The four warmest years in the last 110 were recorded in the 1980s, with the first seven months of 1988 break-

... The role of clouds is one of the great unknowns in predicting climate change associated with the buildup of greenhouse gases.

ing all records. Whereas climatologists have defined one-third of the summer days between 1951 and 1980 as hotter than normal, recent records suggest that in the 1990s we can expect two-thirds of summer days to fall in that category. Does this prove that we are in a greenhouse warming trend? If 1989 is cooler, does that mean the warming trend is over? The answer to both questions is probably not. What else can we look for?

The greenhouse theory predicts that we will see a nonuniform warming of the globe, with greater temperature increases at the poles, since heat flows spontaneously from the large, warm equatorial regions to the smaller, cold polar areas. Also, as warming occurs one would expect melting of highly reflective ice and snow and greater heat absorption by the newly exposed, darker land and water. While there are relatively few long-term temperature data from the polar regions, indirect information suggests that permafrost in some areas may have warmed up by as much as seven degrees F, substantially more than the global averages, during the past century. The observed warming does have the general latitudinal distribution predicted by theory, but differs in some details. Certainly we should carefully observe the distribution of warming and pay special attention to high and low latitudes, where larger, more easily observed increases in temperature are likely. Another clue we should search for in the greenhouse fingerprint is the poleward migration of plant and animal species, and the loss of heat-intolerant species near the warmer margins of their range. Similarly, we can anticipate that warming will vary with altitude



*James Hansen, NASA
Goddard Institute for
Space Studies.*



*Stephen H. Schneider,
National Center for
Atmospheric Research.*



*Sykuro Manabe,
National Oceanic and
Atmospheric Administra-
tion Environmental
Research Laboratories,
Princeton University.*

above the earth in a manner that depends on the distribution of greenhouse gases.

A highly likely outcome of global warming is a rise in sea levels, not only because water expands as it warms, but also because of added volume from the melting of snow and glaciers on land. In fact, records show that sea level is rising at a rate of a bit more than one-half an inch per decade. If greenhouse warming is occurring, this rate can be expected to accelerate to the point where sea level could be one to four feet higher by 2050. Because there is a lag before the effects of atmospheric warming are fully realized, continued additions of greenhouse gases at the present rate will have committed the earth by as early as 2030 to this increase in sea-level rise. Coastal areas will be seriously affected. The United States is currently experiencing beach erosion along three-quarters of its coastline and can expect further losses. Research by Stephen Leatherman at the University of Maryland shows that barrier islands, which protect coasts, are especially vulnerable to sea-level rises of this magnitude. Other researchers have warned of the potential loss of highly productive estuaries and coastal wetlands and the wildlife and marine fisheries they support. Saltwater intrusion into coastal urban groundwater supplies, as well as loss of valuable coastal buildings and damage to highways, sewage treatment plants, and other infrastructure of coastal cities are also likely.

The largest and fastest computers in the world are now trying to model the complex relationships between the atmosphere and the oceans. Although it is exceedingly difficult to predict the detailed regional effects of the projected warming pattern on the weather, researchers foresee significant changes in precipitation and in the intensity and frequency of storm events. We know for certain that the temperature difference between the equator and the poles plays an important role in determining continental weather patterns. Most of the computer models predict that as this temperature difference decreases, precipitation will decline in the mid-continental regions and move toward the poles and the coasts. Sykuro Manabe of the National Oceanic and Atmospheric Administration laboratory at Princeton has developed extensive models that predict changes in soil moisture and temperature and he projects considerable mid-continental summer dryness for most of the important food-growing regions of the middle latitudes, including

the United States grain belt. While the 1988 droughts in the United States and China are consistent with the models, it is not possible to link single-season events to the global warming. Droughts of this magnitude have occurred before; but they would have to happen with increasing frequency to be considered part of the greenhouse fingerprint. It will also be useful to determine the extent to which desertification can be linked to global warming.

Scientists such as Stephen Schneider at the National Center for Atmospheric Research are just beginning to try to model the effect of global warming on storm intensity and frequency. Because tropical storms such as hurricanes and typhoons derive their heat from the oceans, it seems reasonable that they should increase in severity as the oceans warm. During the 1983 El Niño oscillation in the southern Pacific, the altered interaction between ocean currents and the atmosphere produced weather changes around the globe, including drought in Africa and Australia, changing monsoon patterns for the Indian subcontinent, and torrential flooding along the California coast.

Finally, there are uncertainties and possible complex interactions that the fertile minds of scientists have conjured up but not yet placed within the context of the greenhouse fingerprint. For example, what function will clouds have in a warmer world? One would assume that more water would evaporate as the oceans heated up, producing more clouds that would reflect sunlight. The lessened sunlight should help reduce the warming. Recent studies have found, however, that while low-lying clouds do have this effect, the infrared-absorbing property of higher ones outweighs the reflective losses and has a net warming effect. But because no one is certain whether warming oceans will mean more high clouds or low ones, the role of clouds is one of the great unknowns in predicting climate change associated with the buildup of greenhouse gases.

Among still other uncertainties is where nearly half the carbon dioxide that is released into the atmosphere goes. It is assumed that it dissolves in the ocean, but ocean circulation and the biological cycling of carbon are still not very well understood. We know even less about the sources of the rising amounts of atmospheric methane. Part of the increase appears to be related to our agricultural practices. Could some be arising from the warming itself, as anaerobic bacteria increase their

metabolic activity or thawing tundra begins to release the vast stores of trapped methane? Are there surprises ahead for us like those that occurred with the Antarctic ozone hole? Walter Broecker at Columbia University has raised the possibility that changes may not be gradual, but sudden and discontinuous. He has suggested that ocean currents may suddenly shift (as happened in the El Niño event) in response to temperature changes. Were the Gulf Stream, for example, to shift south, we could witness the anomaly of a colder Europe in a warmer world.

Over time the range of conjecture can be expected to narrow, as researchers obtain new information and refine and test their models. There are in fact two very important observations that help to put the greenhouse effect into a larger context.

The first came to light recently (1987) when a Soviet team drilled an ice core two thousand meters deep near its research station at Vostok, in Antarctica. French researchers cooperated in analyzing air samples trapped in the ice and determined their age. From isotope data it was then possible to estimate the global temperature at the time each sample was trapped. The findings were intriguing. Over the past 160,000 years, carbon dioxide levels have varied directly with temperature. During a very warm interglacial period 130,000 years ago, carbon dioxide levels were just under 300 parts per million (ppm). Levels dropped to around 200 ppm during the last great ice age, then climbed to 280 ppm as the world entered the current interglacial warm spell. In only 150 years, we have raised the level to 350 ppm, with more than half of this rise occurring in the past thirty years. It is not possible to determine from the ice core data whether atmospheric carbon dioxide levels cause or follow temperature changes, but that the two are correlated there can be no doubt. What these measurements suggest is that the rate of change in temperature projected by the greenhouse theory is three to ten times faster than any of which we have knowledge—and that by 2030 we may well have brought about temperatures higher than have occurred in 160 millennia.

The second critical natural greenhouse experiment has also been completed with unambiguous results. The atmosphere of our sister planet, Venus, is 98 percent carbon dioxide. Several probes from earth have traversed that atmosphere and reached the planet's surface, which lies beneath a heavy layer of clouds. Each of the probes was destroyed—not by hostile

forces, but by the searing 800-degree-F temperature of the Venusian heat trap. Even were we to burn all our known fossil fuel reserves, increasing the carbon dioxide of our own atmosphere five- to tenfold, we would raise the concentration to only a few tenths of one percent. While this would increase the earth's temperature by several tens of degrees rather than the hundreds observed on Venus, relatively few species

... Is the observed temperature rise caused by the buildup of greenhouse gases? The answer is a resounding "maybe."

would be able to adapt to such a change. Instead of worrying that we might one day run out of fossil fuels, we might take a lesson from our sister planet and realize that we cannot afford to burn all we have.

We must keep such lessons in mind as we conduct our own planet's greenhouse experiment. While we watch for an unambiguous greenhouse warning signal, we need to call on the knowledge we have to fashion a response. Learning to use fossil fuels twice as efficiently as we now do would put our economy and standard of living on the same basis that Western Europe now enjoys. This improved energy-efficiency—combined with replacing coal with natural gas, which produces half the carbon dioxide per unit of energy, and rapidly reducing the use of CFCs during the next decade—would slow the rate of global warming while we develop solar and other noncarbon-dioxide-producing energy technologies. These actions would place our society on a path of sustainable and environmentally sound economic development. It is essential that we begin this task immediately as the insurance we need, just in case the greenhouse fingerprint appears clearer and sooner than expected. ●

William Moomaw is the director of the Climate, Energy and Pollution Program at the World Resources Institute in Washington, D. C., and has taught in the chemistry department at Williams College, where he was the director of the environmental studies program.