

MEMORANDUM TO THE PRESIDENT

From: F. Sherwood Rowland

Subject: Climate Change and its Consequences

PROBLEM

The Earth's climate is changing, in large part because of the activities of humankind. The simplest measure of this change is the average temperature of the Earth's surface, which has risen approximately 0.7 degree Celsius over the past century, with most of the increase occurring in the past two decades. In other words, the Earth is undergoing global warming. The simplest predictor of this climate change is the steady growth of the amount of carbon dioxide (CO₂) in the atmosphere. The concentration of CO₂, the most important greenhouse gas, has increased by more than 16 percent in the past 40 years and by more than 30 percent since the beginning of the industrial revolution 200 years ago. This additional CO₂ comes from the burning of coal, oil, and natural gases, which together account for about 85 percent of the industrial energy used by humans.

Although there are several consequences of climate change other than this increase in global average temperature, the most significant fact as we face the future is that scientists have, at best, an imperfect understanding of the global climate system. The possibility exists for noticeable deterioration of the climate in the United States even on a decadal time scale. Furthermore, unless the drivers of climate change are successful-

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ly addressed and controlled, no future stabilization point can be identified against the otherwise inexorable warming of the globe. As CO₂ continues to accumulate,

doubling and then tripling in concentration, the expected warming will continue to increase. The further this proceeds, the greater the possibility that new chemical or physical processes will be triggered that release still more greenhouse gases. Many of the time scales for these processes, both human and geophysical, are decades to centuries in length, and major efforts must be begun before any irreversible processes begin.

BACKGROUND

Changes in Atmospheric Composition

Abundant evidence exists that the composition of the Earth's atmosphere has changed substantially during the 20th century—especially in the last few decades:

Carbon dioxide. The atmospheric concentration of CO₂, which was 280 parts per million by volume (ppm) in 1800, had increased to 315 ppm in 1958 and is now 368 ppm.

Methane. Atmospheric methane increased from 0.70 ppm in 1800 to 1.52 ppm in 1978 and is now 1.78 ppm. Important emissions sources for methane influenced by humankind include the cultivation of rice, with release to the atmosphere through the plants themselves while the rice fields are inundated, and releases from ruminant mammals, such as cows.

Nitrous oxide. The concentration of atmospheric nitrous oxide has grown from 0.270 ppm in 1800 to 0.300 ppm in 1980 and 0.315 ppm currently. Much of this increase appears to be related to the greatly expanded usage of nitrogenous fertilizers in agriculture.

Chlorofluorocarbons (CFCs). Atmospheric concentrations of the human-made CFCs have increased from zero in 1900 to 540 parts per trillion by volume (ppt) now for CFC-12. For CFC-11 the concentration increased from zero to 270 ppt, for CFC-13 to 85 ppt, and for carbon tetrachloride to 100 ppt. All of the CFCs have been synthesized as essentially inert gases for various technological uses, each of which eventually involves release to the atmosphere of the unchanged molecules.

Tropospheric ozone. The concentration of ozone near the Earth's surface has increased during the past century by a factor of 5–8 in the Northern Hemisphere summer and by a factor of 2–4 in the Northern Hemisphere winter and during both seasons in the Southern Hemisphere. The added surface ozone is an important deleterious component of urban smog, arising from the mechanization of urban transportation. The formation of this ozone involves sunlight together with the release from automobiles of nitrogen oxides, carbon monoxide, and simple hydrocarbons, such as ethylene, acetylene, and many others.

Stratospheric ozone. The stratosphere contains about 90 percent of all ozone, and average concentrations there have been reduced since 1975 by 5–10 percent in the north temperate latitudes (depending upon the season) and much more drastically in the polar regions. For example, in early spring, ozone levels over Antarctica—colloquially described as the Antarctic ozone hole—now regularly reach only 35 percent of the values found for the same seasonal period in the 1960s. These losses have been conclusively established, by direct atmospheric measurements, to be caused by the release of atomic chlorine and bromine from CFCs and related molecules.

The Natural Greenhouse Effect

For the past million years, the Earth has had an average surface temperature varying between about 6 and 14 degrees C (and similar values for eons before that). For the past 10,000 years until the mid-19th century, the global average surface temperature had been relatively steady around 14 degrees C. The Earth constantly receives energy from the sun and must give off an equivalent amount of energy to space so as not to undergo a rapid increase in temperature. The radiation emitted from the sun occurs largely in the visible wavelengths (red to violet, between 700 and 400 nanometers (nm)), in the near-infrared (greater than 700 nm), and 5 percent in the ultraviolet (less than 400 nm). Because there is a 20-fold difference in the surface temperatures of the sun and the Earth, the radiation from the latter is emitted at 20-fold longer wavelengths, in the far-infrared (around 10,000 nm). The amount of energy given off increases rapidly with temperature, about 160,000 times more intense per unit of surface area for the sun than for the Earth.

A straightforward physical calculation can be made of the expected average surface temperature of the Earth from three known quantities, if all of the far-infrared radiation emitted from Earth's surface escapes to space:

- the surface temperature of the sun (5,800 degrees C);
- the distance of the Earth from the sun (93 million miles); and
- the albedo of Earth (30 percent), which is the fraction of sunlight—including the solar infrared and ultraviolet—reflected from the Earth directly back to space without ever being absorbed.

The result of this calculation is an average surface temperature for the Earth of -18 degrees C—clearly much lower than the real temperature. This difference of about 32 degrees C is the natural greenhouse effect, a phenomenon that has been present on Earth for millions of years.

The Enhanced Greenhouse Effect

The flaw in the calculation described above is the assumption that all of the infrared radiation emitted by the Earth escapes directly to space. However, some of it does not because atmospheric molecules containing three or more atoms can absorb radiation with wavelengths in the 5–20 micron range. For example, carbon dioxide, methane, nitrous oxide, CFC-12, CFC-11, water and ozone, among others, trap infrared radiation. Because the main components of the atmosphere (nitrogen, 78.0 percent; oxygen, 21.0 percent; and argon, 0.9 percent) do not absorb infrared radiation, the concentrations of gases present only in trace amounts control the escape of infrared radiation to space. However, these molecular absorptions are quite specific for each compound, so that some wavelengths are absorbed quite strongly by carbon dioxide, methane, or other gases while others are not absorbed appreciably by any of these trace species; such infrared radiation does escape directly to space. Observations from Earth-observing space satellites confirm that wavelengths absorbed by carbon dioxide and methane, among other gases, are greatly reduced in intensity. Because the natural greenhouse effect is well-known, the concern expressed over the last several decades about the accumulation of greenhouse gases in the atmosphere has not been about the existence of a greenhouse effect but rather about the effects of the

added concentrations of CO₂ and the other trace gases in bringing about a still larger discrepancy—an enhanced greenhouse effect, with the difference between observed and calculated global average surface temperatures rising from 32 degrees C to 33 or 35 degrees C. It is worth noting that when the corresponding planetary parameters for Mars are used, the observed and calculated average surface temperatures are in agreement. The Martian atmosphere, of course, is much thinner (0.7 percent as many molecules) than that of Earth, and essentially all wavelengths in the far-infrared escape directly to space. On the other hand, Venus is many hundreds of degrees warmer than it appears from the simple calculation because its atmosphere is 93 times as thick as Earth's, with 95 percent of the molecules being CO₂. In addition, Venus's surface is continually covered by clouds of sulfuric acid droplets, which also intercept infrared radiation.

Recent Global Increase in Temperature

The instrumentation for accurate quantitative recording of temperatures only dates back about two centuries, and thermometers with geographical coverage widespread enough to permit an accurate estimate of global average surface temperatures was only attained around 1870. Since that time, the average global temperature has risen about 0.7 degree C, with much of that increase coming after 1975. The decade of the 1990s is the warmest decade since thermometry became widespread. Over the past 20 years, in addition to using thermometers, temperatures have been inferred from satellite measurements 500 miles from the Earth's surface. The average temperatures recorded from a broad swath across the lower stratosphere indicate an average decrease of about 2 degrees C in the past two decades—in general agreement with the summed expectations from observed increases in atmospheric CO₂ and from decreases in ozone concentrations in the lower stratosphere. Because the satellite instrument also records responses from a broad swath of the troposphere and these swaths are slightly different when the instrument is looking at the Earth in the nadir and from an angle, attempts have been made to infer near-surface temperatures by subtracting one swath from the other. Although widely publicized over the past decade as showing no temperature increase since 1979, several flaws have been identified in the handling of these satellite data, and the utility to date of this technique for measurement of actual surface temperatures is minimal.

Temperatures have also been inferred retrospectively for layers in glacial ice cores and deep sea sediment cores. The composition of water in an ice core can be used to evaluate the temperature at which the water vapor condensed into liquid water or ice before final precipitation. Air constitutes approximately 10 percent by volume of such ice cores, trapped at the time the weight of snow and ice above has closed off further diffusion through channels in the ice. In Antarctic coastal regions with heavy snowfall, measurements over the past thousand years show nearly constant concentrations of carbon dioxide, methane, and nitrous oxide up to the 19th century and then accelerating increases in concentration that mesh with the direct air measurements made in the past 20–40 years. The isotopic variations in the ice itself distinguish summer from winter and allow a direct count of the passage of the years. By considering a variety of such reconstructed temperature scales, the 1990s also appears to be the warmest decade in the last millennium.

Although over the past million years the Earth's climate has oscillated rather wildly, with a series of ice ages in which all of Canada, the Great Lakes, and Scandinavia were buried under about one mile of glacial ice, during the most recent 10,000 years, the Earth's average temperature has been quite stable. However, within this general stability, substantial regional variations have taken place. For example, about 7,000 years ago most of the current Sahara desert region received annual rainfall of more than 8 inches per year, but it now receives less than 0.5 inch per year. In the much colder, high altitude regions of Greenland and Antarctica—also deserts in terms of yearly precipitation—the ice cores trace back through the series of ice ages and interglacials that have periodically gripped the Earth. The two-mile-deep Vostok ice core (about 800 miles from the South Pole) has provided such information covering the past 420,000 years. During these extended time intervals, carbon dioxide and methane have exhibited lower concentrations during the ice age periods, mimicking the temperature changes themselves. For both of these gases, the atmospheric concentrations in the year 2000 are the highest recorded for the preceding 420 millennia.

During the time between initial snowfall as a porous, fluffy mass and the accumulation of sufficient weight of snow and ice to produce a compact ice core, the gases trapped within the snow can diffuse both upward and downward. The downward diffusion of atmospheric nitrogen within an ice core (in this case, from Greenland) carries a complex isotopic signal that involves both gravitation-

al separation and the temperature at the surface. The consequence is a measure of the rate of change in surface temperature. During the time period from 16,000 to 10,000 years ago, as the Earth emerged from the most recent ice age, the cores indicate two intervals when the average surface temperature increased very sharply by about 2 degrees C within a single decade. The usual scenario associated with prospective global warming and climate change is of gradual, steady warming. However, these ice core results indicate that under some conditions of changing climate, the transition may be rapid—the appropriate description of the climate control mechanism may be that of an “off/on switch” rather than a smoothly varying “dial.”

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Modeling the Atmosphere

General circulation models (GCMs) are attempts to place within an understandable framework a computational system that reproduces as many as possible of the measured data pertaining to the motions and composition of the atmosphere and the oceans. Basically, the Earth receives more solar radiation per unit area in the tropics than in the temperate and polar zones, creating a gradient of temperature decreasing away from the equator. The flow of heat from hot to cold regions is transported poleward in roughly equal measure by the motions of the atmosphere and by the ocean currents. One simple required test of such a model is its ability to reproduce, through changing angles of incoming solar radiation and variations in the length of daylight, the temperature and other differences between summer and winter. A more difficult test is the simulation of the succession of ice ages over the past million years when the whole globe was alternatively cooler by as much as 5–8 degrees C interspersed with periods characterized by temperatures much like the present. The best current explanation for these drastic changes in global temperature is the variation of solar intensity received during the summer in the high northern latitudes because of periodic cyclic variations under the influence of the multiple gravitational attractions among the sun and the other planets in the solar system. This understanding, put forth 60 years ago by the Yugoslavian scientist Milankovitch, involves three parameters in the sun-Earth relationship:

- the angle of inclination of the Earth toward its orbital plane (now 23.5

degrees);

- the month of the year when the Earth is closest to the sun (now January); and
- the extent of deviation of the Earth's elliptical orbit from circular, (now 3 percent).

The timing of the ice ages agrees with this explanation when measured against fluctuations in the amount of solar energy arriving in the summer at a latitude of 65 degrees North. However, the differences in the amounts of energy arriving are not in themselves able to produce the large temperature changes needed for agreement with the observations. Because the needed amplifying factors triggered by these initial solar energy inputs have not been satisfactorily identified, the evidence for the explanation through the Milankovitch cycles remains only circumstantial.

The Effects of Increasing Trace Gas Concentrations: Feedbacks

In a typical GCM calculation, the model is run with 280 ppm of CO₂ present and then again with 560 ppm of CO₂, a doubling of its content. The infrared wavelengths that CO₂ can absorb are absorbed very near Earth's surface with 280 ppm present and are then re-emitted in all directions in amounts determined by the ambient temperature at that altitude. Then they are reabsorbed at a higher altitude by CO₂ and re-emitted again and again, until finally somewhere in the lower stratosphere at a temperature of perhaps -60 degrees C, some lesser amount of radiation makes it out to space at this wavelength. When the model simulation is repeated with 560 ppm of CO₂, the final escape is even more hindered, and the temperature of the surface must increase to maintain the balance between incoming solar energy and outgoing terrestrial infrared energy. This balance is not quite perfect, and the almost imperceptible excess of incoming solar over outgoing terrestrial energy accumulates over the decades into a higher surface temperature, (i.e., the enhanced greenhouse effect).

After the average global surface temperature has increased, three feedback effects come into play. First, the increased temperature causes an increase in the rate of evaporation of water about 6 percent for each degree C. Because water is itself a greenhouse gas, its higher concentration also traps more outgoing terres-

trial infrared radiation, requiring a higher temperature to produce more infrared emissions in compensation. Second, in the polar regions at the margins between water and ice, a warming trend will replace the highly reflective ice (albedo ~ 0.8 – 0.9) with strongly absorbing water (albedo ~ 0.1). Consequently, less incoming solar radiation will be reflected back into space, and the additional energy absorption will add to the temperature rise. The margin between bare ground and snow cover behaves similarly, again furnishing a positive feedback to augment the original temperature rise. These effects are included in the GCMs, with the consequence that predictions of global temperature change for the polar regions are larger than for the global average. Such preferential warming of the polar regions tends to reduce the latitudinal temperature gradient and diminishes the need for poleward heat transport through the atmosphere and the oceans. A lessening of the Gulf Stream's strength could induce temperature decreases in western Europe in the midst of average global warming.

The Effects of Clouds

The most problematic part of GCM calculations concerns the effects of clouds. As with the greenhouse gases, they, too, absorb outgoing terrestrial infrared radiation. But, in addition, the tops of clouds reflect incoming visible radiation back into space and also emit infrared radiation upward. Because the average temperature decreases with increasing altitude in the troposphere, the top of a high cloud is much colder—and emits less infrared radiation—than the top of a low cloud. With a low cloud, the top reflects incoming solar to space and, because its temperature is not much colder than the ground beneath, emits almost as much infrared radiation as it intercepts. As a result, the formation of a low cloud with increasing temperature represents a negative feedback, working against the temperature increase. However, with the formation of a high cloud, the lower temperature on top reduces the outgoing flux of terrestrial infrared radiation (relative to surface emissions) more than it reflects incoming solar radiation to space. The result is a positive feedback. The real situation is even more complicated because it is not obvious whether an increase in atmospheric temperature will increase or decrease cloudiness or whether it will change the altitudes of the clouds. The individual cloud feedbacks can theoretically be either negative or positive and may well have a different sign over different geographic regions, depending upon the particular circumstances.

The Year 2100

Future calculations with GCMs carry with them not only the manifold imperfections in their simulation of the real world, but also the unknown behavior of the human population during each period. Within these limits, the expected increase in global average temperature by the year 2100 lies between about 1 degree and 3.5 degrees C. In more detailed predictions for specific regions, the models frequently diverge from one another. For example, using the most recent results from the Canadian GCM, the prediction for the southeastern United States is for an average temperature increase of more than 6 degrees C by 2100 and an even greater increase in the (Dis)Comfort Index from the combination of heat and humidity. Other model calculations do not show such large changes but still indicate substantial warming in the southeast. The underlying difficulty in policy considerations is that none of the available information indicates that the Canadian model (or any of the other models) is wrong—the regional information is simply not precise enough to distinguish among conflicting, plausible models.

In the future, water will play an even more important role than it does now, with increasing global population and the consequent heavy demands for increased agricultural production. A warming climate will have many consequences for water use on the planet. For example, as the atmosphere warms, heat is transferred to the ocean, and it in turn warms—and expands. The warming of the ocean's surface is slowly transmitted downward so the total expansion response of the oceans requires many decades—even centuries—for completion. Additional sea-level rise can also result if the total amount of land-supported ice is diminished and redistributed into the oceans. The estimated sea-level rise by 2100 varies from about 1 to 3 feet. In another example, the increase in surface temperature will cause the rate of water evaporation to increase, with a corollary increase in rainfall. At the same time, a quickening loss of soil moisture could bring about alternating conditions of hotter and drier periods with more intense rainstorms. When hurricanes are traced back to their oceanic birthplaces, the water there is found to be 27 degrees C or warmer—the developing storm requires additional energy to grow to hurricane strength, water vapor condensing into droplets releases the needed energy, and warmer water produces water vapor more rapidly. Plausible arguments can be made for both more big storms and for greater intensity of these storms. In California, most of the precipitation now comes down as rain and snow in the autumn and winter seasons. The winter

snow pack then serves as the major water source during the dry spring and summer. With higher winter temperatures, precipitation is more likely to come down as rain than as snow, and the state could have lessened snowpacks and therefore less available water in the summer and heavier runoff and flooding during the winter rains.

RECOMMENDATIONS

As the various examples cited above indicate, a changing climate offers numerous possibilities for extensive, possibly severe, impacts upon society. However, the present and likely situation in the immediate future is that the capability of prediction from the best atmospheric models will not provide accurate smaller-scale forecasts. We need to have much more computational power available, with climate modeling as one of the major applications. Simultaneously, we need to have an appropriate, consistent set of detailed measurements made on a regional scale so that the differential outputs from various choices of input parameters fed into the climate models can be tested for significance in comparison with real world data. Under these circumstances, we should be preparing for adaptation to more rapid changes than have been routinely encountered in the past, while still endeavoring to improve our predictive abilities.

None of the human or geophysical responses to climate change can take place quickly. Even alterations of the transportation fleet takes place over decades, as old cars and trucks are replaced by more fuel-efficient vehicles, or, as is happening now in the United States, by sport utility vehicles with significantly enlarged fuel needs. Most industrial power plants going into operation in the year 2000 will be nearing the end of their useful life in the decade 2040–2050. Conversely, more than half of the current power plants globally will still be in operation 20 to 25 years from now. Harbor facilities that will still be in use in 2075 should be built to accommodate the coming sea-level rise. The removal of the greenhouse gases from the atmosphere by natural processes occurs on a time scale of a half-century or more. Because of the long-term nature of such alterations, the need to begin the process is urgent.

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much more serious by the year 2050 and even more so by 2100. Currently, the best models of the climate system agree reasonably well on hemispheric-scale features, but they have progressive difficulties as the regions for which predictions are desired become smaller

and more specific. Nevertheless, these forward-looking projections indicate the kinds of effects that may arise in the near future. We need to be exploring all of the potential avenues of response to climate change, and we need to do it now because the development of long-term solutions will require decades to develop and decades to put into action.