GREENHOUSE EFFECT

[*For an introduction to* Greenhouse Effect, *see articles on* Carbon Dioxide *and* Global Warming.]

A Scientific Analysis

The term *greenhouse effect* refers broadly to the partial trapping by the atmosphere of radiation from the Earth's surface, leading to a surface temperature that is larger than would be the case without the atmosphere. While the atmosphere is relatively transparent to shortwave radiation (sunlight), it is nearly opaque to infrared radiation, owing to the presence of certain trace gases and of clouds. Much of the infrared radiation passing upward from the Earth's surface is absorbed and reradiated, both upward and downward. Because the surface therefore receives not just solar radiation but also infrared radiation from the atmosphere and clouds, it is much warmer than it would be in the absence of the atmosphere. (Actual greenhouses work mostly by preventing the upward *convection*—not radiation—of heat received from the sun, so that the term *greenhouse effect* is something of a misnomer.)

The most important greenhouse gas in the atmosphere is *water vapor*. Along with clouds, composed of water drops or ice crystals, water vapor plays a key role in trapping outgoing terrestrial radiation. But because water vapor responds rapidly to changing conditions, water is treated as a feedback in the climate system, not an external forcing. It is generally believed that water vapor and clouds are the most important feedbacks in the climate system, at least on time scales of thousands of years or less. [*See* Clouds; *and* Water Vapor.]

Next to water in all its phases, the important greenhouse substances in the atmosphere include *carbon dioxide*, *methane*, *nitrous oxide*, *ozone*, and various *chlorofluorocarbons* (CFCs). The CFCs are entirely of anthropogenic origin. Carbon dioxide is thought to respond to changes in sources and sinks over a time scale of from forty to several hundred years, while methane has an inherent time scale of about eight years. The ozone concentration peaks in the middle stratosphere, where it filters out most of the harmful, very shortwave (ultraviolet) radiation from the sun. Although its lifetime is short, ozone's concentration is affected by the presence of other trace gases, notably chlorine, which is in turn related to the chlorofluorocarbons, which have very long lifetimes. Analysis of gas bubbles trapped in polar ice shows that carbon dioxide and methane had somewhat lower concentrations during the ice ages but had quite stable concentrations from the end of the last major glaciation until the beginning of the Industrial Revolution. The carbon dioxide concentration of the atmosphere has been increasing since the early nineteenth century, owing to our consumption of fossil fuels and to deforestation, and is expected to reach twice its natural, postglacial value sometime in the twenty-first century. [*See* Deforestation.]

The concentration of methane increased even more rapidly over the past two centuries (but now seems to be stabilizing), for reasons that are less clear but possibly related to the influence of human activities, which are also affecting the concentrations of ozone, nitrous oxide, and the chlorofluorocarbons. Because of the important role these gases play in the greenhouse effect, it is feared that their increasing concentrations may lead to noticeable global warming. [*See* Carbon Dioxide;

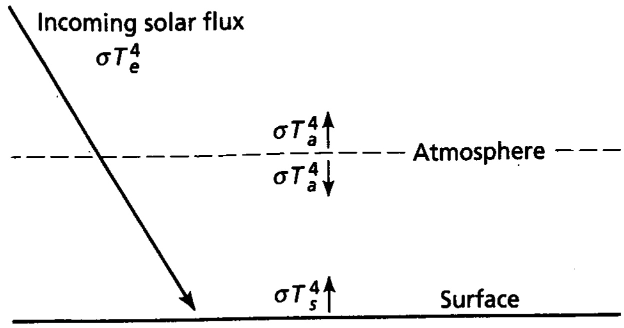
Chlorofluorocarbons; Methane; Nitrous Oxide; *and* Ozone.]

The recognition that certain trace gases may play an important role in determining the temperature of the Earth's surface and atmosphere dates back two centuries, to the French scientist Jean Baptiste-Joseph Fourier (1768–1830), who described the surface warming in terms of a "hothouse." There followed many others who contributed to the understanding of the greenhouse effect, among them John Tyndall in England (1820–1893), who measured the absorption of infrared radiation by carbon dioxide and water vapor, and, most importantly, Svante Arrhenius (1859–1927), the Swedish Nobel laureate in chemistry who performed the first quantitative estimates of the surface temperature change that would result from changes in atmospheric carbon dioxide concentration (see Arrhenius, 1896). [*See the biography of Arrhenius.*]

Basic Physics of the Greenhouse Effect. Averaged over a year and over the whole area of the Earth, about 340 watts per square meter of solar radiant energy enters the top of the atmosphere, mostly in the form of visible light. Suppose there were no atmosphere, and that none of the incoming radiation were reflected back to space. Then, since in the long run the Earth must be in thermal equilibrium, it has to radiate as much energy back to space as it receives from the sun. According to the Stefan-Boltzmann equation, the amount of radiation emitted by a perfect radiator is given by σT^4, where σ is the Stefan-Boltzmann constant (about 5.67×10^{-8} $Wm^{-2}\ K^{-4}$) and T is the temperature of the emitter. Thus, in equilibrium, the surface temperature of the Earth would be given by $\sigma T^4 = 340\ Wm^{-2}$. Solving for T gives a temperature of about 278 kelvins, or 5°C. This is considerably colder than the observed average temperature of the Earth's surface, which is more like 288 kelvins, or 15°C.

A photo of the Earth taken from space dramatically illustrates how clouds reflect a great deal of the incoming solar radiation. In fact, on average the clouds—and, less importantly, the Earth's surface itself—reflect about 30 percent of the incoming solar radiation, reducing the amount absorbed to about 240 Wm^{-2}. Solving the Stefan-Boltzmann equation again gives a surface temperature of about 255 kelvins, or −18°C, even colder than before. It is the greenhouse effect of trace gases and clouds that accounts for the much larger observed average temperature.

The basic idea of the greenhouse effect is illustrated by Figure 1. Suppose that the atmosphere and clouds can be represented by a single layer of gas and clouds at some temperature T_a and that this layer of gas and clouds can be treated as a perfect emitter. The layer therefore emits radiant energy both upward and downward at the rate σT_a^4, while the surface emits upward



Greenhouse Effect. Figure 1. A Simple Model of the Greenhouse Effect.

Incoming solar radiation is absorbed at the surface, which, in the absence of an atmosphere, would have an equilibrium temperature T_e. Infrared radiation emitted by the surface is absorbed by the atmosphere, whose temperature is T_a. The atmosphere in turn radiates infrared radiation both upward to space and downward to the surface. $T_a = T_s = 2^{1/4}\ T_e$.

at the rate σT_s^4, where T_s is the surface temperature. At the top of the atmosphere, the total outgoing radiative flux, given by $\sigma T_a{}^4$, must balance the net incoming solar flux of 240 Wm^{-2}, giving $T_a = 255$ kelvins. But the surface receives energy from *both* the sun *and* the atmosphere, and the thermal equilibrium of the surface requires that

$$\sigma T_s^4 = 240\ Wm^{-2} + \sigma T_a^4 = 480\ Wm^{-2}.$$

Solving for T_s gives a surface temperature now of 303 kelvins, or 30°C. Although this result is now much warmer than the observed temperature, this simple model illustrates the basic concept of the greenhouse effect. One aspect of the whole system that is of special interest is the contradictory role of clouds in climate. On the one hand, they reflect much solar radiation back to space, tending to cool the climate; on the other hand, they are important contributors to the greenhouse effect, which warms the climate.

The model of the greenhouse effect illustrated by Figure 1 is obviously a gross oversimplification. To perform an accurate estimate of the greenhouse effect, we have to divide the atmosphere into many layers, each with its own temperature and each radiating only a fraction of what the Stefan-Boltzmann law gives (this fraction is called the *emissivity*). This fraction depends crucially on the amount of greenhouse gases and clouds in the layer, and it determines not only how much radiation the layer can emit but also what fraction of the radiation passing through it from other layers can be absorbed. We also have to take into account that the atmosphere is not completely transparent to sunlight; clouds and water vapor absorb some of the incoming solar radiation. When all these things are accounted for in sophisticated radiative transfer models, the equilibrium surface temperature works out to be about 350 kelvins or about 80°C. But the equilibrium temperature decreases quite rapidly with altitude, reaching a minimum of around 210 kelvins (about −60°C) about eight miles above the surface.

The greenhouse effect is so large that, in the absence of other processes, it would make the surface of the Earth very hot indeed. But the rapid decrease of temperature with altitude in the radiative equilibrium state cannot be sustained because it is unstable to convective overturning, as first recognized by R. Emden in 1913 (see Goody and Yung, 1989 for details). Cool air aloft sinks and warm air from lower down rises until a new equilibrium is achieved, characterized by a vertical rate of decrease of temperature that is nearly neutrally stable to convective overturning. In the Earth's atmosphere, water usually condenses in the rising convective plumes, and much of the condensed water falls to the surface as precipitation. When the water condenses, the latent heat of vaporization is released to the air, making it warmer than it would be otherwise. The result of this moist convection is the establishment of a vertical rate of decrease of temperature that is nearly neutrally stable to the moist convection. This vertical rate of decrease of temperature is referred to as the *moist adiabatic lapse rate*, and it varies with both altitude and temperature. Figure 2 shows a pair of moist adiabats for the Earth's atmosphere.

Because of the greenhouse effect, acting in concert with cumulus convection, the actual state of much of the Earth's atmosphere is very nearly one of *radiative-convective equilibrium*. (Such a state does not exist, however, over middle- and high-latitude continents in winter.) In such a state, convection carries much of the heat flux from the surface to the lower atmosphere, but as one goes higher in the atmosphere, the radiative fluxes become progressively more important. At 10–12 kilometers above the surface, the convective fluxes cease, and above that altitude, the atmosphere is nearly in pure radiative equilibrium. In the tropics, almost all of the heat flux from the surface to the lowest layers of the atmosphere is carried by convection.

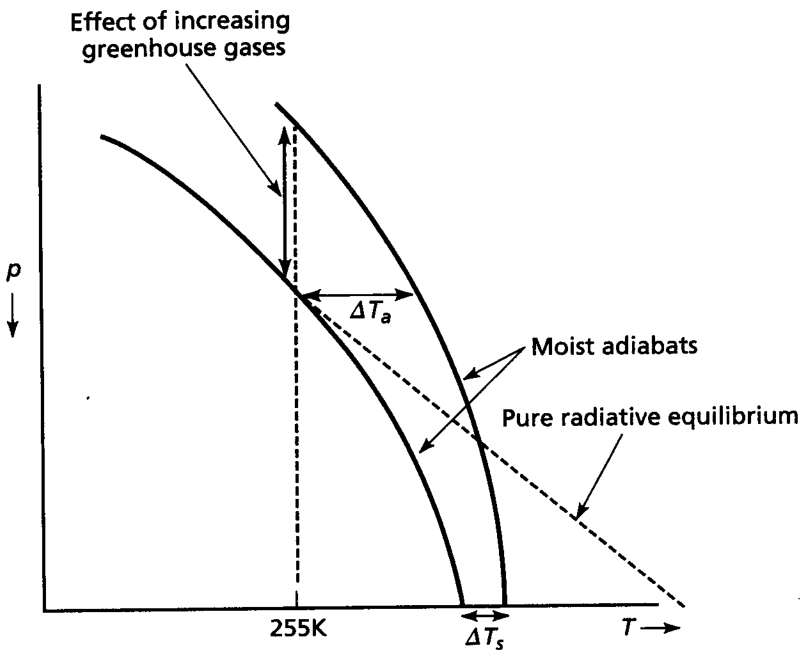
The most important consequence of the convective heat transfer is that the surface is much cooler than it would be in pure radiative equilibrium. The surface is still receiving about 240 Wm^{-2} from the sun and an even larger amount from back-radiation from the atmosphere, but it is losing most of that energy by convection, not directly by radiation. In connection with the reduced emission from the surface, the surface temperature is lower. Conversely, the atmosphere is receiving energy from the convection and thus must be warmer than it would be in pure radiative equilibrium, so it is cooling radiatively. For example, the tropical troposphere cools at an average rate of about 2°C per day by radiation.

The cooling effect of convection on the Earth's surface is illustrated in Figure 2. First, note that there is a particular altitude at which the temperature happens to be equal to the temperature the surface would have in the absence of an atmosphere (i.e., 255 kelvins). Most of the greenhouse gases are below this altitude. In the present climate, this altitude is around 6 km above the surface. In pure radiative equilibrium, the temperature would increase very rapidly downward from this level. But because of convection, the temperature actually increases downward much more slowly (i.e., along a moist adiabat), giving a much lower surface temperature. The actual operation of the greenhouse effect is more complicated and subtle than is usually recognized. However, excellent treatments in the literature have existed for many years (e.g., Goody and Yung, 1989).

There is one particularly interesting complication in this picture: It is the convection itself that largely determines the distribution of the two most important greenhouse substances, water vapor and clouds. Thus, real radiative-convective equilibrium is a highly interactive process.

Response of the Greenhouse Effect to Increasing Concentrations of Trace Gases. The basic physics underlying the sensitivity of global temperature to greenhouse gas concentration can also be seen in Figure 2. The key point is that the temperature of the atmosphere and surface is most sensitive to changes in the concentrations of greenhouse gases near the level at which $T =$ 255 kelvins. Changing the concentration of greenhouse gases or clouds at and above this level will change the altitude where $T = 255$ kelvins. (Changing the amount of greenhouse gases lower in the atmosphere will have less effect.) For example, increasing the concentration of carbon dioxide or methane will move upward the altitude at which $T = 255$ kelvins. Following a moist adiabat down to the surface shows that the surface temperature will increase, but because of the divergence of moist adiabats with altitude, the surface temperature increase will be only about half the temperature increase in the upper troposphere (less in the tropics and more in polar regions).

If changes in greenhouse gas concentration were the only factor involved, it would be straightforward to calculate the resulting temperature change in the atmosphere and at the surface. For example, doubling the carbon dioxide concentration would increase the global average surface temperature by about 1°C. The complexity of the climate problem arises from the great number of feedbacks in the climate system. For example, raising the temperature of the atmosphere may increase the amount of water vapor—a greenhouse gas—thereby giving an even greater increase in temperature.



Greenhouse Effect. FIGURE 2. The Effect of Convection and of Increasing Concentration of Greenhouse Gases.

Pressure decreases upward and temperature increases to the right. The two thin, solid lines are moist adiabats; convection keeps the temperature profile close to curves of this shape. In the absence of convection, the temperature would be close to a state of radiative equilibrium, shown by the thick dashed line. Increasing greenhouse gases, particularly in the upper troposphere, near and above the level at which the temperature equals 225K, moves the altitude at which $T = 255$K upward. This causes an increase in upper tropospheric temperature of δT_a and a corresponding increase of δT_s in the surface temperature.

Greenhouse Feedbacks. As is apparent from Figure 2 and from the discussion in the preceding section, the greenhouse effect is particularly sensitive to changes in greenhouse gases and clouds near and above the altitude at which the actual temperature is equal to the effective emission temperature (255 kelvins). It is well established from more detailed calculations (e.g., Lindzen, 1997) that tropospheric and surface temperature are somewhat more sensitive to changes in greenhouse gases and clouds in the upper troposphere and lower stratosphere. Thus one of the great challenges in predicting and understanding climate change is to understand the response of upper-tropospheric and lower-stratospheric variable greenhouse constituents—namely, water vapor and clouds—to changes in forcing. It is the uncertainty in this response that has driven much of the controversy surrounding the issue of global warming.

Two major physical processes control the amount of water vapor (and, indirectly, clouds) in the Earth's atmosphere: the circulation of the atmosphere and microphysical processes within the cloud. The latter determine how much cloud water (very small droplets or ice crystals effectively suspended in the air) is converted to precipitation and how much of the precipitation reevaporates before reaching the surface. We know that if all cloud water were converted to precipitation, all of which fell to the ground without reevaporation, the atmosphere would be far drier than observed; conversely, if precipitation did not occur at all, the atmosphere would become saturated with water vapor and filled with cloud. Reality lies somewhere in between. The great sensitivity of actual water vapor concentration to the details of cloud microphysics was first demonstrated by Emanuel (1991) and Renno et al. (1994).

The circulation of the atmosphere also exerts a strong influence on the distribution of water vapor. Over much of the Earth, particularly in the subtropics, air near the effective emission altitude is subsiding, having detrained from convective clouds thousands of kilometers away (Sun and Lindzen, 1993). Only within 1–2 kilometers of the Earth's surface in these regions is air directly influenced by the local sea surface. Some of this subsiding air is observed to be extremely dry, implying that little addition of water occurred from the time the air originally left the tops of tall cumulonimbus clouds (Spencer and Braswell, 1997). In other places, the descending air is more moist, implying that some mixing with other airstreams has occurred, or that the air has been moistened by evaporating precipitation or outflow from shallower clouds.

Satellite images demonstrate that a disproportionate amount of radiation leaving the Earth originates in these dry, subtropical "windows." Thus the net greenhouse effect of the planet as well as its sensitivity to changes in forcing can be sensitive to the relative size of these regions of subsidence and to the degree of mixing of moist air into such regions.

Unfortunately, there is little quantitative understanding of many of the processes that have been described here, and there is considerable reason to be skeptical of the ability of current global climate models to handle these processes correctly. Not a single existing climate model contains even the most rudimentary representation of the fundamental cloud microphysical processes operating within cumulus clouds (Emanuel and Zivkovic-Rothman, 1999). For example, it is well known that the efficiency of conversion of cloud water to precipitation increases strongly with temperature (e.g., see Sun and Lindzen, 1993), yet this is not contained in the convective representations used in climate models. Moreover, as demonstrated by Tompkins and Emanuel (2000), the vertical resolution of climate models is inadequate, resulting in incorrect prediction of water vapor and reduced sensitivity of water vapor content to cloud microphysics (Emanuel and Zivkovic-Rothman, 1999). These problems also result in an artificially strong coupling between water vapor fluctuations at the surface and aloft in climate simulations (Sun and Held, 1996). Problems of this nature will have to be tackled before we can have confidence in model simulations of global climate change.

Summary. Greenhouse gases work by absorbing some of the infrared radiation that would otherwise pass directly from the Earth's surface to space and reradiating part of this energy back down toward the surface, which thus receives radiation not only from the sun but from the atmosphere and clouds as well. The last two require warming in the atmosphere to operate. The most important greenhouse constituents of the atmosphere are water vapor and clouds, but water vapor cycles so quickly through the atmosphere that its concentration is usually regarded as a feedback, rather than a forcing, in the climate system. Next to water vapor and clouds, carbon dioxide, methane, nitrous oxides, and ozone are the most important greenhouse constituents. Rising levels of these constituents raise concern that the Earth's climate may warm appreciably. Just how much warming occurs depends crucially on the response of water vapor and clouds to changing climate, but the physics controlling these important feedbacks is still inadequately understood or modeled. Thus while the basic physics of the greenhouse effect is well understood, quantitative estimates of its sensitivity to climate change are hampered by poor understanding of certain key physical processes and by inadequate measurement of clouds and water vapor in the upper troposphere.

[*See also* Aerosols; Albedo; Atmosphere Dynamics; Atmosphere Structure and Evolution; Atmospheric Chemistry; Climate Change; Global Warming; Hydrologic Cycle; *and* Sun.]

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