Greenhouse effect

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Key Concepts

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- The greenhouse effect results from the warming of a planet's atmosphere due to trapping of incoming solar radiation.
- Water vapor, carbon dioxide, and ozone, as well as methane, CFCs, and nitrous oxide, are all considered to be greenhouse gases, but each varies in its capacity to absorb radiation.
- Scientists use past data to model the impacts of current and future increases in human-caused emissions of additional greenhouse gases, including higher temperatures, a rise in sea level, and more extreme weather events.
- Planets with documented greenhouse effects include Venus, Earth, and Mars.

The ability of a planetary atmosphere to inhibit heat loss from the planet's surface, thereby enhancing the surface warming that is produced by the absorption of solar radiation. The greenhouse effect arises in planetary atmospheres that are heated by solar radiation. For the greenhouse effect to work efficiently, the planet's atmosphere must be relatively transparent to sunlight at visible wavelengths so that significant amounts of solar radiation can penetrate to the ground. Also, the atmosphere must be opaque at thermal wavelengths to prevent thermal radiation emitted by the ground from escaping directly to space. The principle is similar to a thermal blanket, which also limits heat loss by conduction and convection. In recent decades, the term has also become associated with the issues of global warming and climate change induced by human activity. *See also:* **Atmosphere (/content/atmosphere/058800)**; **Solar radiation (/content/solar-radiation/633700)**

Of the terrestrial planets, Venus has by far the strongest greenhouse effect. Though only about 1% of the incident solar radiation penetrates to the ground, the thermal opacity of Venus's atmosphere, which is 100 times more massive than the Earth's and composed mostly of carbon dioxide, is exceedingly large. As a result, the greenhouse effect on Venus is about 15 times greater than on Earth. The trapped solar radiation on Venus generates a surface temperature of nearly 460°C (860°F), which is hot enough to melt lead and vaporize mercury. This is 500°C (900°F) hotter than the surface would be if it were simply in thermal equilibrium with the global mean solar energy absorbed by Venus (−40°C, −40°F), without benefit of the greenhouse effect. For the Earth, the strength of the greenhouse warming effect is a more modest 33°C (60°F), due primarily to the thermal opacity of atmospheric water vapor, clouds, and carbon dioxide. The trapped sunlight makes the global mean surface temperature of the Earth a relatively comfortable 15°C (59°F) instead of an otherwise frigid −18°C (−1°F). On Mars, a very thin carbon dioxide atmosphere (Mars atmospheric pressure = 0.01 atm; Earth's atmosphere = 1 atm) can muster only a few degrees (about 5°C or 9°F) of greenhouse warming. Meanwhile, on Mercury, which has no tangible atmosphere, there is no greenhouse effect at all. Mercury's surface temperature is determined solely by local thermal equilibrium with the absorbed sunlight.

It is believed that in the early stages of the solar system, when the Sun had only about 75% of its present luminosity, Venus may also have had an ocean and an atmosphere much like that of the Earth. However, in its early days Venus was apparently unable to sequester its store of carbon in the form of limestone, as did the Earth. As a result, carbon dioxide emitted from volcanic eruptions continued to accumulate in the Venusian atmosphere, increasing its greenhouse effect and evaporating more and more water vapor into the atmosphere to further magnify the growing strength of its greenhouse. Eventually all the ocean water was vaporized, and the water vapor was carried high into the atmosphere where most of it was photolyzed and lost to space. Perhaps the climate disaster on Venus can be attributed to the lack of appropriate life forms that might have limited the buildup of carbon dioxide. In any case, Venus stands as an example of a runaway greenhouse effect that has rendered the planet inhospitable to life. *See also:* **Mars (/content/mars/407700)**; **Mercury (planet) (/content/mercury-planet/415700)**; **Venus (/content/venus/730100)**

Mechanism

The basic concept of the greenhouse effect was first described in 1824 by French mathematician and physicist Joseph Fourier, who performed experiments on atmospheric heat flow and pondered the question of how the Earth stays warm enough for plant and animal life to thrive. Fourier realized that much of the thermal radiation emitted by the Earth's surface was being absorbed within the Earth's atmosphere, and that some of this absorbed radiation was being reemitted downward, providing additional warming of the ground surface besides that due to the direct absorption of solar energy.

In 1863, Irish physicist John Tyndall provided experimental support for Fourier's greenhouse idea and demonstrated by means of quantitative spectroscopy that common atmospheric trace gases, such as water vapor, ozone, and carbon dioxide, are strong absorbers and emitters of thermal radiant energy but are transparent to visible sunlight. It was clear to Tyndall that water vapor was the strongest absorber of thermal radiation and, therefore, the most influential atmospheric gas controlling the Earth's surface temperature. Thus, atmospheric water vapor and carbon dioxide absorb thermal radiation emitted by the ground surface, but then, in order to conserve energy, the absorbed thermal radiation would have to be locally reradiated, such that the reemitted radiation would now be going in both the upward and downward directions. The principal components of air, nitrogen and oxygen, were found to be radiatively inactive, serving instead as the atmospheric framework where water vapor and carbon dioxide can exert their influence. Based on his understanding of the radiative properties of absorptive gases in the atmosphere, Tyndall speculated in 1861 that a reduction in atmospheric carbon dioxide could induce an ice-age climate.

Relying on the work of Tyndall and on careful measurements of heat transmission through the atmosphere compiled by the American astronomer Samuel Langley, the Swedish chemist and physicist Svante Arrhenius was the first to develop a quantitative mathematical framework that is quite similar to our current understanding of how the terrestrial greenhouse effect keeps the surface temperature some 33°C (or 60°F) warmer than it otherwise would be if the Earth had no atmosphere, or if the atmosphere had no greenhouse gases such as water vapor and carbon dioxide that absorb thermal radiation. In 1896, Arrhenius published his heat-balance calculations of the Earth's sensitivity to carbon dioxide change. Given that Arrhenius's basic interest was to explain the likely causes of ice-age climate, his greenhouse model was successful. He showed that reducing atmospheric carbon dioxide by a third would cool the global surface temperatures by

−3°C (−5.5°F), and that doubling carbon dioxide would cause the tropical latitudes to warm by 5°C (9°F), with somewhat larger warming in polar regions. These results are in remarkably close agreement with current expectations for global climate change in response to carbon dioxide forcing. *See also:* **Spectroscopy (/content/spectroscopy/642600)**

Large epochal (ice-age) variability is evident in the terrestrial climate record. This implies that the greenhouse effect on Earth operates differently from the static, or at least slowly evolving, carbon dioxide greenhouses on Venus and Mars. Ice ages occur as the result of epochal changes in the atmospheric concentration of carbon dioxide over geological time scales, initiated by Milankovitch variations of the Earth orbital parameters that alter the relative seasonal distribution of incident solar radiation within the polar regions. There radiative forcing changes are further magnified by concomitant changes in atmospheric water vapor (which is even more effective in absorbing thermal radiation compared to carbon dioxide). Thus, the largest contributor to the terrestrial greenhouse effect is in fact atmospheric water vapor, but it is strongly dependent on temperature. Because of this, and also because condensing water vapor produces clouds which typically cool the Earth, there is strong coupling and interaction between the amount of atmospheric water vapor and temperature.

This aspect of water-vapor behavior was noted by the American geologist Thomas Chamberlin who, in 1905, described the greenhouse contribution by water vapor as a positive feedback mechanism. Thus, surface heating due to solar radiation, or another agent such as carbon dioxide, raises the surface temperature and evaporates more water vapor which, in turn, produces additional heating and further evaporation. When the heat source is taken away, excess water vapor precipitates from the atmosphere, reducing its contribution to the greenhouse effect to produce further cooling. This feedback interaction converges and, in the process, achieves a significantly larger temperature change than would be the case if the amount of atmospheric water vapor had remained constant. The net result is that carbon dioxide becomes the controlling factor of long-term change in the terrestrial greenhouse effect, but the resulting change in temperature is magnified by the positive feedback action of water vapor.

In addition to water vapor, many other feedback interactions operate in the Earth's climate system and impact the sensitivity of the climate response to an applied radiative forcing. Determining the relative strengths of feedback interactions between clouds, aerosols, snow, ice, and vegetation, including the effects of energy exchange between the atmosphere and ocean, is an actively pursued research topic in current climate modeling. Current best estimates from climate modeling results show that without feedback effects, a doubling of atmospheric carbon dioxide will raise the global surface temperature by 1.2–1.3°C (2.2–2.4°F), but that the net feedback magnification due to water vapor, snow/ice melting, and cloud changes magnifies the no-feedback result by approximately a factor of 3.

Interestingly, carbon dioxide accounts for approximately 7°C (13°F) of the total 33°C (60°F) terrestrial greenhouse effect, and the other noncondensing (at current climate temperatures) greenhouse gases such as ozone, methane, nitrous oxide, and anthropogenic chlorofluorocarbons add another 3–4°C (5–7°F) of greenhouse strength. In this context, the noncondensing greenhouse gases can be thought of as providing the core forcing for the Earth's greenhouse effect. The larger greenhouse contribution by water vapor and clouds may then be considered to represent the feedback response that magnifies the core forcing by an overall feedback factor of about 3. This distinction helps to identify more clearly the causes and effects in an otherwise highly interactive climate system. *See also:* **Climate modeling (/content/climate-modeling/140350)**; **Climate modification (/content/climate-modification/140400)**

Clouds absorb thermal radiation at all wavelengths of the spectrum. Because of this, clouds are important contributors to the terrestrial greenhouse effect. The greenhouse efficiency of a greenhouse contributor depends on how strongly it absorbs thermal radiation, and on how weakly the absorbed thermal radiation is reemitted to space. The laws of physics require that the emissivity of a substance must be equal to its absorptivity. However, while the absorptivity of the absorbing material need not depend on the temperature of the absorbing material, the emission of thermal radiation has explicit dependence on temperature. Thus a cloud near the ground is a poor contributor to the greenhouse effect because it absorbs and re-emits thermal radiation at nearly the same temperature. A cirrus cloud, on the other hand, is a strong contributor to the terrestrial greenhouse effect because it absorbs the relatively high-temperature radiation emitted from the ground surface, but being at cold temperature itself, is only able to emit a small fraction of the absorbed radiation out to space, thus very effectively trapping heat within the atmosphere. *See also:* **Cloud (/content/cloud/142000)**; **Heat balance, terrestrial atmospheric (/content/heat-balance-terrestrial-atmospheric/310500)**

Since the greenhouse effect is a radiative process, it is possible to analyze the amount of radiation that is being absorbed and emitted by the different components of the climate system by means of radiative transfer calculations, and thus determine the relative importance of each greenhouse constituent. The results of such radiative modeling analysis by G. A. Schmidt and colleagues showed that of the total 33°C (60°F) greenhouse effect, about 50% is contributed by water vapor, 25% by clouds, 20% by carbon dioxide, and the remaining 5% is due to methane, nitrous oxide, ozone, and the chlorofluorocarbon gases. These radiative contributions to the greenhouse effect can then be separated into two groups: the non-condensing greenhouse gases (carbon dioxide and the other minor trace gases), and the condensing species (water vapor and clouds).

It is not just the greenhouse gases that constitute the greenhouse effect. Also very important is the atmospheric temperature profile that is established by the combined effort of atmospheric dynamics, thermodynamics, and the radiative heating and cooling. In fact, it is the atmospheric temperature profile along with the vertical distribution of the greenhouse gases that determines the full magnitude of the terrestrial greenhouse effect. If only radiation were the sole means of energy transport, the terrestrial greenhouse effect would be twice as large, or about 66°C (120°F) warmer than the no-atmosphere reference temperature of –18°C (or about 0°F). As it is, the atmospheric temperature gradient that is implied by a radiation-only atmosphere is far too unstable against convection. As convection sets in, this transports energy upward to equalize the temperature imbalance, establishing the terrestrial greenhouse effect at the 33°C (60°F) level.

A. A. Lacis and colleagues demonstrated the volatile nature of the terrestrial greenhouse effect in a climate modeling experiment in which all of the non-condensing greenhouse gases were zeroed out. The resulting water vapor and cloud only greenhouse effect collapsed rapidly with the water vapor quickly condensing and raining out, plunging the climate of Earth into an ice ball state. This climate modeling experiment reinforces our understanding that it is the radiative forcing effects of the noncondensing greenhouse gases (of which carbon dioxide contributes 80%) that provide the sustaining support structure for the terrestrial greenhouse effect. From this it can be concluded that atmospheric carbon dioxide acts as a thermostat to regulate the equilibrium temperature of Earth.

Within the million-year geological context, volcanoes are the principal source of atmospheric carbon dioxide, and the weathering of rocks is the principal sink. Fifty million years ago, atmospheric carbon dioxide is believed to have been as high as 2000 parts per million, a time when there was no permanent ice even in the polar regions. About 35 million years ago, when the atmospheric carbon dioxide level had decreased to about 450 parts per million, permanent glaciation began to appear in Antarctica. Ice core measurements covering the past 400,000 years show atmospheric carbon dioxide levels to have varied between about 180 parts per million during the greatest extent of continental ice, to about 280 parts per million during the warmer inter-glacial periods.

The current level of atmospheric carbon dioxide stands near 390 parts per million, and it is increasing by about 2 parts per million as the direct result of human industrial activity. Given that it is the non-condensing greenhouse gases that provide the sustaining support for the terrestrial greenhouse effect, it follows therefore that the strength of the terrestrial greenhouse effect is increasing as the atmospheric level of carbon dioxide increases. It is only the large ocean heat capacity that keeps delaying the inevitable increase in global temperature that is being built into the climate system.

Given accurate knowledge of the atmospheric concentration of greenhouse gases, their impact on the strength of the atmospheric greenhouse effect can be accurately calculated using the extensive spectroscopic databases that are available now. Inasmuch as the term “greenhouse effect” refers to determining the radiative efficiency of trapping solar heat at the ground surface by the absorption and emission of thermal radiation, a moderate computational effort can provide the answer. Insofar as human activity induces global warming and climate change, it is necessary to incorporate the uncertainties that are associated with atmospheric feedback processes and with atmosphere/ocean dynamical interactions that contribute to greenhouse efficiency. At present, it is necessary to rely on general circulation climate models to determine the feedback contribution (due mostly to clouds and water vapor) to the total atmospheric greenhouse effect, since remote sensing measurements capable of measuring feedback-related water vapor and cloud changes are not currently available. *See also:* **Climate modeling (/content/climate-modeling/140350)**; **Atmospheric general circulation (/content/atmospheric-general-circulation/059500)**; **Remote sensing (/content/remote-sensing/580900)**

Human impact

The modern approach to studying Earth's climate and the human impact on climate change began in the 1930s with the work of Guy Callendar, a British engineer who systematically documented the time trend of anthropogenic fossil-fuel use and linked it to the corresponding increase in atmospheric carbon dioxide. Having had available to him the precise spectroscopic measurements of the absorption characteristics of water vapor, carbon dioxide, and other heat-absorbing gases, Callendar could link his estimates of carbon dioxide increase with the 0.4°C (0.7°F) temperature increase recorded in the 50 years prior to 1950. In 1958 Charles Keeling, a research chemist at Scripps Institute in California, began making high-precision measurements of carbon dioxide accumulation in the atmosphere. This ushered in a new era of precise measurement and documentation of the atmospheric increases of carbon dioxide and other greenhouse gases such as methane and nitrous oxide. The new measurement techniques were subsequently applied to measuring the precise gaseous composition of air bubbles trapped in glacial ice, thereby extending knowledge of atmospheric composition over time scales going back 420,000 years based on the Antarctic Vostoc ice-core data. The measurements show that atmospheric concentrations of carbon dioxide increased from a preindustrial 280 parts per million in 1850 to the present value of nearly 390 ppm. In geological context, during the last ice age when the global temperature was about 5°C (9°F) colder, atmospheric carbon dioxide was at levels near 180 ppm.

Both Arrhenius and Callendar considered the projected global temperature increases due to anthropogenic carbon dioxide buildup as likely to be beneficial in warming the cold regions of the Earth. But human-induced contributions to climate change are not necessarily benign. For example, discovery of an ozone hole in the Antarctic in the early 1980s pushed the world community to the 1987 Montreal agreement to phase out production of chlorofluorocarbons to reverse ozone destruction in the stratosphere caused by these compounds. As a by-product, this also helped to reduce the rate of increase of the anthropogenic greenhouse forcing. *See also:* **Stratosphere (/content/stratosphere/659100)**; **Stratospheric ozone (/content/stratospheric-ozone/757477)**

In late 1997, the world community met in Kyoto to consider what could be done to help stabilize and curtail the steady increase in fossil-fuel use and the resulting increase in the strength of greenhouse forcing. To date, there have been no agreements to stabilize or reduce fossil-fuel use. However, there are good reasons to be concerned: (1) The projected global warming is much larger than anything previously experienced in human history. (2) The climate response to a globally uniform forcing is not necessarily uniform and may include large regional fluctuations. (3) Extreme events, both droughts and floods, are more likely with the stronger hydrological cycle of a warmer Earth. (4) The inevitable rise in sea level will put low-lying coastal areas at increased risk. (5) Unanticipated changes in global climate could occur if the climate system were to exceed some critical threshold that is beyond the modeling capability of current climate models.

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Test Your Understanding

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1. Explain a positive greenhouse-effect feedback process.
2. Compare the strength of the greenhouse effect on Earth and on Venus. Explain the cause of this strength difference between the two planets.
3. Critical Thinking: Which group has the largest impact on global temperature associated with the greenhouse effect: condensing or noncondensing greenhouse gases? Explain your answer.

Links to Primary Literature

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American Institute of Physics: The Carbon Dioxide Greenhouse Effect (https://www.aip.org/history/climate/co2.htm)

Intergovernmental Panel on Climate Change: What is the Greenhouse Effect? (https://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-3.html)

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