Greenhouse effect

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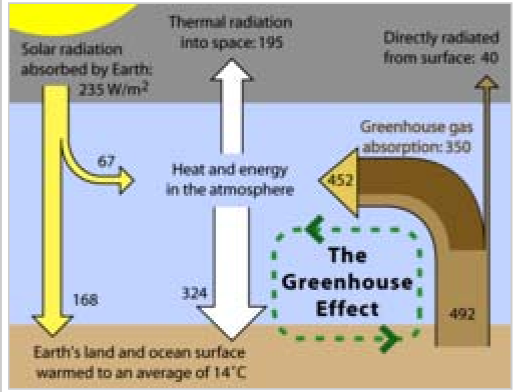
The **greenhouse effect** is the process in which the emission of infrared radiation by the atmosphere warms a planet's surface. The name comes from an analogy with the warming of air inside a greenhouse compared to the air outside the greenhouse. The Earth's average surface temperature is about 33°C warmer than it would be without the greenhouse effect.[1] The greenhouse effect was discovered by Joseph Fourier in 1829 and first investigated quantitatively by Svante Arrhenius in 1896. In addition to the Earth, Mars and especially Venus have greenhouse effects.



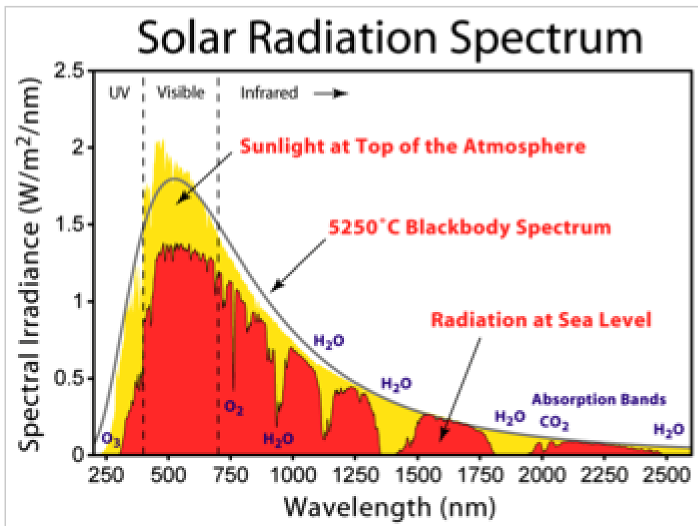
A schematic representation of the exchanges of energy between outer space, the Earth's atmosphere, and the Earth surface. The ability of the atmosphere to capture and recycle energy emitted by the Earth surface is the defining characteristic of the greenhouse effect.

Contents

Basic mechanism

See also: Radiative forcing

The Earth receives energy from the Sun in the form of radiation. The Earth reflects about 30% of the incoming solar radiation. The remaining 70% is absorbed, warming the land, atmosphere and oceans. For the Earth's temperature to be in steady state so that the earth does not rapidly heat or cool, this absorbed solar radiation must be very nearly balanced by energy radiated back to space in the infrared wavelengths. Since the intensity of infrared radiation increases with increasing temperature, one can think of the Earth's temperature as being determined by the infrared flux needed to balance the absorbed solar flux. The visible solar radiation mostly heats the surface, not the atmosphere, whereas most of the infrared radiation escaping to space is emitted from the upper atmosphere, not the surface. The infrared photons emitted by the surface are mostly absorbed in the atmosphere by greenhouse gases and clouds and do not escape directly to space.



Solar radiation at top of atmosphere and at Earth's surface.

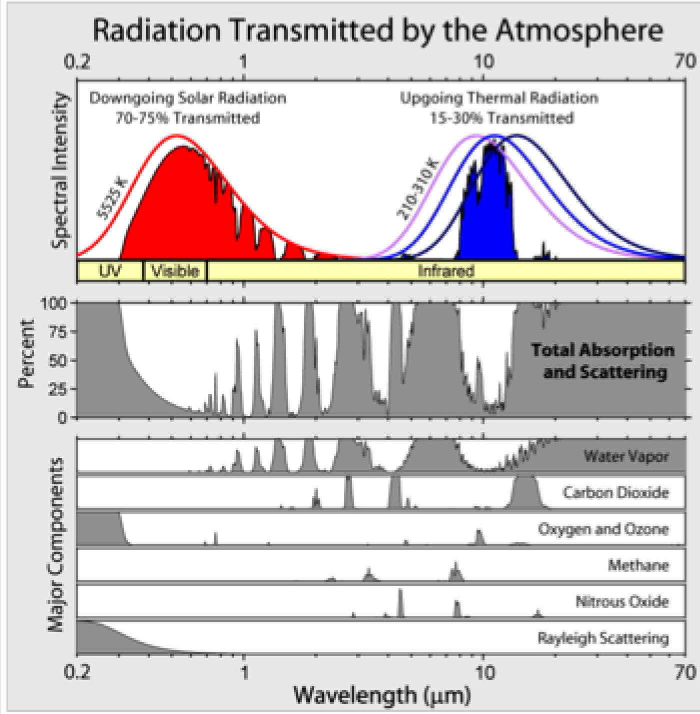
The reason this warms the surface is most easily understood by starting with a simplified model of a purely radiative greenhouse effect that ignores energy transfer in the atmosphere by convection (sensible heat transport) and by the evaporation and condensation of water vapor (latent heat transport). In this purely radiative case, one can think of the atmosphere as emitting infrared radiation both upwards and downwards. The upward infrared flux emitted by the surface must balance not only the absorbed solar flux but also this downward infrared flux emitted by the atmosphere. The surface temperature will rise until it generates thermal radiation equivalent to the sum of the incoming solar and infrared radiation.

A more realistic picture taking into account the convective and latent heat fluxes is somewhat more complex. But the following simple model captures the essence. The starting point is to note that the opacity of the atmosphere to infrared radiation determines the height in the atmosphere from which most of the photons emitted to space are emitted. If the atmosphere is more opaque, the typical photon escaping to space will be emitted from higher in the atmosphere, because one then has to go to higher altitudes to *see* out to space in the infrared. Since the emission of infrared radiation is a function of temperature, it is the temperature of the atmosphere at this emission level that is effectively determined by the requirement that the emitted flux balance the absorbed solar flux.

But the temperature of the atmosphere generally decreases with height above the surface, at a rate of roughly 6.5 °C per kilometer on average, until one reaches the stratosphere 10-15 km above the surface. (Most infrared photons escaping to space are emitted by the troposphere, the region bounded by the surface and the stratosphere, so we can ignore the stratosphere in this simple picture.) A very simple model, but one that proves to be remarkably useful, involves the assumption that this temperature profile is simply fixed, by the non-radiative energy fluxes. Given the temperature at the emission level of the infrared flux escaping to space, one then computes the surface temperature by increasing temperature at the rate of 6.5 °C per kilometer, the environmental lapse rate, until one reaches the surface. The more opaque the atmosphere, and the higher the emission level of the escaping infrared radiation, the warmer the surface, since one then needs to follow this lapse rate over a larger distance in the vertical. While less intuitive than the purely radiative greenhouse effect, this less familiar *radiative-convective* picture is the starting point for most discussions of the greenhouse effect in the climate modeling literature.

The term "greenhouse effect" is a source of confusion in that actual greenhouses do not warm by this same mechanism.[2]

Greenhouse gases



Pattern of absorption bands generated by various greenhouse gases and their impact on both solar radiation and upgoing thermal radiation from the Earth's surface. Note that a greater quantity of upgoing radiation is absorbed, which contributes to the greenhouse effect.

Quantum mechanics provides the basis for computing the interactions between molecules and radiation. Most of this interaction occurs when the frequency of the radiation closely matches that of the spectral lines of the molecule, determined by the quantization of the modes of vibration and rotation of the molecule. (The electronic excitations are generally not relevant for infrared radiation, as they require energy larger than that in an infrared photon.)

The width of a spectral line is an important element in understanding its importance for the absorption of radiation. In the Earth’s atmosphere these spectral widths are primarily determined by “pressure broadening”, which is the distortion of the spectrum due to the collision with another molecule. Most of the infrared absorption in the atmosphere can be thought of as occurring while two molecules are colliding. The absorption due to a photon interacting with a lone molecule is relatively small. This three-body aspect of the problem, one photon and two molecules, makes direct quantum mechanical computation for molecules of interest more challenging. Careful laboratory spectroscopic measurements, rather than *ab initio* quantum mechanical computations, provide the basis for most of the radiative transfer calculations used in studies of the atmosphere.

The molecules/atoms that constitute the bulk of the atmosphere; oxygen (O_2), nitrogen (N_2) and argon; do not interact with infrared radiation significantly. While the oxygen and nitrogen molecules can vibrate, because of their symmetry these vibrations do not create any transient charge separation. Without such a transient dipole moment, they can neither absorb nor emit infrared radiation. In the Earth’s atmosphere, the dominant infrared absorbing gases are water vapor, carbon dioxide, and ozone (O_3). The same molecules are also the dominant infrared emitting molecules. CO_2 and O_3 have "floppy" vibrational motions whose quantum states can be excited by collisions at energies encountered in the atmosphere. For example, carbon dioxide is a linear molecule, but it has an important vibrational mode in which the molecule bends with the carbon in the middle moving one way and the oxygens on the ends moving the other way, creating some charge separation, a dipole moment, thus carbon dioxide molecules can absorb IR radiation. Collisions will immediately transfer this energy to heating the surrounding gas. On the other hand, other CO2 molecules will be vibrationally excited by collisions. Roughly 5% of CO2 molecules are vibrationally excited at room temperature and it is this 5% that radiates. A substantial part of the greenhouse effect due to carbon dioxide exists because this vibration is easily excited by infrared radiation. CO2 has two other vibrational modes. The symmetric stretch does not radiate, and the asymmetric stretch is at too high a frequency to be effectively excited by atmospheric temperature collisions, although it does contribute to absorption of IR radiation. The vibrational modes of water are at too high energies to effectively radiate, but do absorb higher frequency IR radiation. Water vapor has a bent shape. It has a permanent dipole moment (the O atom end is electron rich, and the H atoms electron poor) which means that IR light can be emitted and absorbed during rotational transitions, and these transitions can also be produced by collisional energy transfer. Clouds are also very important infrared absorbers. Therefore, water has multiple effects on infrared radiation, through its vapor phase and through its condensed phases. Other absorbers of significance include methane, nitrous oxide and the chlorofluorocarbons.

Discussion of the relative importance of different infrared absorbers is confused by the overlap between the spectral lines due to different gases, widened by pressure broadening. As a result, the absorption due to one gas cannot be thought of as independent of the presence of other gases. One convenient approach is to remove the chosen constituent, leaving all other absorbers, and the temperatures, untouched, and monitoring the infrared radiation escaping to space. The reduction in infrared absorption is then a measure of the importance of that constituent. More precisely, define the greenhouse effect (GE) to be the difference between the infrared radiation that the surface would radiate to space if there were no atmosphere and the actual infrared radiation escaping to space. Then compute the percentage reduction in GE when a constituent is removed. The table below is computed by this method, using a particular 1-dimensional model of the atmosphere. More recent 3D computations lead to similar results.

Gas removed	percent reduction in GE
H_2O	36%
CO_2	12%
O_3	3%

(Source: Ramanathan and Coakley, Rev. Geophys and Space Phys., 16 465 (1978)).[3]

By this particular measure, water vapor can be thought of as providing 36% of the greenhouse effect, and carbon dioxide 12%, but the effect of removal of both of these constituents will be greater than 48%. An additional proviso is that these numbers are computed holding the cloud distribution fixed. But removing water vapor from the atmosphere while holding clouds fixed is not likely to be physically relevant. In addition, the effects of a given gas are typically nonlinear in the amount of that gas, since the absorption by the gas at one level in the atmosphere can remove photons that would otherwise interact with the gas at another altitude. The kinds of estimates presented in the table, while often encountered in the controversies surrounding global warming, must be treated with caution. Different estimates found in different sources typically result from different definitions and do not reflect uncertainties in the underlying radiative transfer.

Positive feedback and runaway greenhouse effect

When the concentration of a greenhouse gas (**A**) is itself a function of temperature, there is a positive feedback from the increase in another greenhouse gas (**B**), whereby increase in B increases the temperature which, in turn, increases the concentration of A, which increases temperatures further, and so on. This feedback is bound to stop, since the overall supply of the gas A must be finite. If this feedback ends after producing a major temperature increase, it is called a **runaway greenhouse effect**.

According to some climate models (Clathrate gun hypothesis), such a runaway greenhouse effect, involving liberation of methane gas from hydrates by global warming, caused the Permian-Triassic extinction event. It is also thought that large quantities of methane could be released from the Siberian tundra as it begins to thaw, methane being 21-times more potent a greenhouse gas than carbon dioxide.[4]

A runaway greenhouse effect involving CO_2 and water vapor may have occurred on Venus. On Venus today there is little water vapor in the atmosphere. If water vapor did contribute to the warmth of Venus at one time, this water is thought to have escaped to space. Venus is sufficiently strongly heated by the Sun that water vapor can rise much higher in the atmosphere and is split into hydrogen and oxygen by ultraviolet light. The hydrogen can then escape from the atmosphere and the oxygen recombines. Carbon dioxide, the dominant greenhouse gas in the current Venusian atmosphere, likely owes its larger concentration to the weakness of carbon recycling as compared to Earth, where the carbon dioxide emitted from volcanoes is efficiently subducted into the Earth by plate tectonics on geologic time scales.[5][6]

Anthropogenic greenhouse effect

CO_2 production from increased industrial activity (fossil fuel burning) and other human activities such as cement production and tropical deforestation has increased the CO_2 concentrations in the atmosphere. Measurements of carbon dioxide amounts from Mauna Loa observatory show that CO_2 has increased from about 313 ppm (parts per million) in 1960 to about 375 ppm in 2005. The current observed amount of CO_2 exceeds the geological record of CO_2 maxima (~300 ppm) from ice core data (Hansen, J., Climatic Change, **68**, 269, 2005 ISSN 0165-0009 (http://www.springerlink.com/content/x283l27781675v51/?p=799ebc88193f4ecfa8ca76f6e28f45d7)).

Because it is a greenhouse gas, elevated CO_2 levels will increase global mean temperature; based on an extensive review of the scientific literature, the Intergovernmental Panel on Climate Change concludes that "*most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*".[7]

Over the past 800,000 years,[8] ice core data shows unambiguously that carbon dixoide has varied from values as low as 180 parts per million (ppm) to the pre-industrial level of 270ppm.[9] Certain paleoclimatologists consider variations in carbon dioxide to be a fundamental factor in controlling climate variations over this time scale.[10]

Real greenhouses

The term 'greenhouse effect' originally came from the greenhouses used for gardening, but it is a misnomer since greenhouses operate differently [1] (http://www.ems.psu.edu/~fraser/Bad/BadGreenhouse.html) [2] (http://www.wmconnolley.org.uk/sci/wood_rw.1909.html). A greenhouse is built of glass; it heats up primarily because the Sun warms the ground inside it, which warms the air near the ground, and this air is prevented from rising and flowing away. The warming inside a greenhouse thus occurs by suppressing convection and turbulent mixing. This can be demonstrated by opening a small window near the roof of a greenhouse: the temperature will drop considerably. It has also been demonstrated experimentally (Wood, 1909): a "greenhouse" built of rock salt (which is transparent to IR) heats up just as one built of glass does. Greenhouses thus work primarily by preventing *convection*; the atmospheric greenhouse effect however reduces *radiation loss*, not convection. It is quite common, however, to find sources (e.g., [3] (http://pangea.stanford.edu/courses/gp025/webbook/07_clement.html) [4] (http://www.ngdc.noaa.gov/paleo/globalwarming/greeneffect.html)) that make the "greenhouse" analogy. Although the primary mechanism for warming greenhouses is the prevention of mixing with the free atmosphere, the radiative properties of the glazing can still be important to commercial growers. With the modern development of new plastic surfaces and glazings for greenhouses, this has permitted construction of greenhouses which selectively control radiation transmittance in order to better control the growing environment [5] (http://ag.arizona.edu/ceac/research/archive/HortGlazing.pdf)PDF (271 KiB).

See also

- Climate forcing

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- Bad Greenhouse http://www.ems.psu.edu/~fraser/Bad/BadGreenhouse.html

Categories: Atmospheric radiation | Climate change feedbacks and causes | Climate forcing | Atmosphere