The **greenhouse effect** is the heating of the surface of a planet or moon due to the presence of an atmosphere containing gases that absorb and emit infrared radiation.
The Greenhouse Effect

SUN

Some solar radiation is reflected by the Earth’s surface and the atmosphere.

ATMOSPHERE

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gases. The effect of this is to warm the surface and the lower atmosphere.

EARTH

Most solar radiation is absorbed by the surface, which warms.

Infrared radiation is emitted from the Earth’s surface.
electromagnetic spectrum
Laws of radiation

1. All objects emit radiant energy

2. Hotter objects radiate more energy per unit area than cooler objects

3. The hotter the radiating body, the shorter the wavelength of maximum radiation
The Stefan–Boltzmann law states that the total energy radiated per unit surface area of a black body in unit time (known variously as the black-body irradiance, energy flux density, radiant flux, or the emissive power) $E^*$ is directly proportional to the fourth power of the black body's thermodynamic temperature $T$ (also called absolute temperature)

$$E^* = \sigma T^4$$

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$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.670400 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4},$$
Published nearly 80 scientific articles, mostly in the Bulletins of the Vienna Academy of Sciences. He is best known for originating a physical power law in 1879 stating that the total radiation from a black body $j^*$ is proportional to the fourth power of its thermodynamic temperature $T$

$$j^* = \sigma T^4$$
Ludwig Boltzmann
1844-1906

Austrian physicist famous for his founding contributions in the fields of statistical mechanics and statistical thermodynamics. He was one of the most important advocates for atomic theory at a time when that scientific model was still highly controversial.
solar constant \((S)\)

Solar luminosity divided by the area of a sphere with the radius of the distance between the Sun and Earth

solar luminosity \(= 3.8 \times 10^{26}\) Watts

Earth-Sun distance \(= 1.49 \times 10^8\) km

\[
S = \frac{3.8 \times 10^{26}}{4\pi (1.49 \times 10^{11})^2}
\]

\(1370\) W/m\(^2\)
\[ S = 1370 \, \text{W/m}^2 \]

Total energy absorbed by Earth:
\[ \text{area} = \pi r^2 \]

Total energy absorbed per unit area of Earth surface:
\[ \frac{S(1-A)}{4} = \frac{1370(1-0.35)}{4} \approx 223 \, \text{W/m}^2 \]
effective, or blackbody, temperature?

applying the laws of radiation…

\[ E^* = \sigma T_e^4 \]

\[ \rightarrow T_e = (E^*/\sigma)^{1/4} \]

\[ = (223 / 5.67 \times 10^{-8})^{1/4} \]

\[ = 251 \text{ K} = -22^\circ\text{C} \]

Present-day global average temperature = 288 K = 15°C
the greenhouse effect

1. Much of the incoming, short wavelength, solar radiation penetrates the atmosphere and heats Earth's surface.

2. Objects on Earth's surface emit long wavelength radiation skyward.

3. Greenhouse gases absorb outgoing, long wavelength, radiation and reradiate some of this energy Earthward, thus trapping heat in the lower atmosphere.
energy balance
near-surface temperature
Global Mean Energy Balance

At the top \( \text{In} = \text{Out} \)

\( 342 \text{ W/m}^2 = 342 \text{ W/m}^2 \)

At the surface \( \text{In} = \text{Out} \)

\( 492 \text{ W/m}^2 = 492 \text{ W/m}^2 \)
lower atmosphere is warmed

Solar Radiation absorbed by Earth: 235 W/m²

Directly radiated from surface: 40

Thermal radiation into space: 195

Heat and energy in the atmosphere: 67

Greenhouse gas absorption: 350

The Greenhouse Effect

Earth's land and ocean surface warmed to an average of 14°C
absorption by greenhouse gases
composition of the atmosphere
composition of the atmosphere

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percent by Volume</th>
<th>Concentration in Parts Per Million (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.084</td>
<td>780,840.0</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>20.946</td>
<td>209,460.0</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
<td>9,340.0</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.037</td>
<td>370.0</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.00182</td>
<td>18.2</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.000524</td>
<td>5.24</td>
</tr>
<tr>
<td>Methane CH₄</td>
<td>0.00015</td>
<td>1.5</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>0.000114</td>
<td>1.14</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>0.00005</td>
<td>0.5</td>
</tr>
</tbody>
</table>
What makes a gas greenhouse gas?

Able to absorb infrared light

• Must have molecular vibration(s)
  - This excludes monoatomic gases as greenhouse gases. (That is why argon, the third most abundant atmospheric constituents is transparent to infrared irradiation)

The molecular vibrations must be non-symmetric, i.e. infrared active

Homonuclear diatomic molecules only have symmetric vibrations. That’s why N$_2$, O$_2$ are not greenhouse gases.
What are the major greenhouse gases?

- $\text{H}_2\text{O}$
- $\text{CO}_2$
- $\text{CH}_4$
- $\text{N}_2\text{O}$
- $\text{O}_3$
- CFCs
- SF6
Enhanced greenhouse effect

When concentrations of greenhouse gases increase, more infrared radiation is returned toward Earth and the surface temperature rises.
The average atmospheric CO$_2$ concentrations observed at Mauna Loa, Hawaii increased approximately 40 ppmv between 1958 and 1995. The small fluctuations in the curve are seasonal variations due primarily to the withdrawal and production of carbon dioxide by terrestrial life. Notice that minimum values occur during the northern hemisphere summers (when global photosynthetic activity is greatest) and maximum values occur six months later.
Methane

Atmospheric methane has increased steadily to present day levels; this increase is highly correlated with human population growth and with related activities, including agricultural practices.
Indicators of the human influence on the atmosphere during the Industrial era

- **Carbon Dioxide concentration**
  - $CO_2$ concentration in ppm over time.

- **Nitrous Oxide concentration**
  - $N_2O$ concentration in ppb over time.

- **Methane concentration**
  - $CH_4$ concentration in ppb over time.

- **Sulfate aerosols deposited in Greenland ice**
  - Sulfur emissions from United States and Europe (Mt S yr$^{-1}$), measured in mg SO$_2$ per tonne of ice over time.
model sensitivity study

![Graph showing the relationship between Global Temperature (°C) and Atmospheric CO₂ (ppm). The graph indicates a positive correlation, with Global Temperature increasing as Atmospheric CO₂ increases.](image)
The greenhouse effect was discovered by Joseph Fourier in the 1820s.
Fourier's observation that the ground temperature of the Earth is increased because of the existence of the atmosphere; a phenomenon that would become known as "the greenhouse effect". Often considered the foundation of climate change science.

Remarques générales sur les Temperatures du globe terrestre et des espaces planétaires

Prior to Tyndall it was widely surmised, but he was first to prove, that the Earth's atmosphere has a Greenhouse Effect.

John Tyndall
1820-1893

measured the infrared absorptive powers of the gases nitrogen, oxygen, water vapor, carbon dioxide, ozone, methane, etc. He concluded that water vapor is the strongest absorber of radiant heat in the atmosphere and is the principal gas controlling air temperature.
John Tyndall


1863 John Tyndall, "On the Relation of Radiant Heat to Aqueous Vapor." *Philosophical Magazine* ser. 4, 26: 30-54.
In 1896, when he published his greenhouse calculation, Arrhenius was Professor of Physics and Rector at the Stockholm Högskola. He was already famous for showing how dissolved salts separate into charged particles ("ions"). In 1903 he was awarded the Nobel Prize in Chemistry for "the extraordinary services he has rendered to the advancement of chemistry by his electrolytic theory of dissociation."
Guy Stewart Callendar
1898-1964

From Quarterly J. Royal Meteorological Society 64, 223 (1938).
From Quarterly J. Royal Meteorological Society 64, 223 (1938).
Growing Blanket of Carbon Dioxide Raises Earth’s Temperature

Earth’s ground temperature is rising 1½ degrees a century as a result of carbon dioxide discharged from the burning of about 2,000,000,000 tons of coal and oil yearly. According to Dr. Gilbert N. Plass of the Johns Hopkins University, this discharge augments a blanket of gas around the world which is raising the temperature in the same manner glass heats a greenhouse. By 2080, he predicts the air’s carbon-dioxide content will double, resulting in an average-temperature rise of at least four percent. If most of man’s industrial growth were over a period of several thousand years, instead of being crowded within the last century, oceans would have absorbed most of the excess carbon dioxide. But because of the slow circulation of the seas, they have had little effect in reducing the amount of the gas as man’s smoke-making abilities have multiplied over the past hundred years.

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