Greenhouse Effect

A simple model of global temperature

Energy incident \( \equiv S \pi R^2 \quad S \equiv 1372 \text{ W/m}^2 \)

Energy reflected \( \equiv \alpha S \pi R^2 \quad \alpha = \text{albedo} = 0.31 \)

Energy re-radiated \( \equiv \tau 4 \pi R^2 T^4 \quad \tau \equiv 5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4 \)

Solve for \( T \quad T = 255\text{K} \quad (-18^\circ \text{C}) \)

Known \( T = +15^\circ \text{C}, \quad 33^\circ \text{C} \text{ higher than model} \)

Why: Greenhouse Effect (Atmosphere transmits incoming radiation; absorbs outgoing radiation)
Earth's Energy Balance

Figure 3.2
Figure 8.8 Global average energy flows between space, the atmosphere, and the earth's surface. Units are watts per square meter of surface area. (Based on Hare, 1985.)

Fig. 4.8 Energy balance of the earth.
History

Early atmosphere of earth ~1000 x more CO\textsubscript{2}
Enabled development of life

$$6 \text{CO}_2 + 6 \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2$$

(Other part of C cycle

$$\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{energy}$$)
Atmospheric carbon dioxide has increased 30% since 1800

Carbon dioxide concentrations over the past 1,000 years determined from ice core records (shown as symbols) appear to have fluctuated little until 1850. Since 1958, air measurements (shown as purple line) taken at Mauna Loa, Hawaii, have supplemented the ice core data. The smooth black curve is based on a 100-year running mean. The inset of the period from 1850 onward shows CO₂ emissions in gigatons (billions of metric tons) per year attributed to burning fossil fuels (shown as a blue line).

Global mean temperature has been on the rise since 1880

Global

Temperature change, °C

Note: Zero is the 1951-80 average temperature. Source: NASA Goddard Institute for Space Studies
What Atmospheric Gases Contribute to Greenhouse Effect?

**Table 8.3 Major Greenhouse Gases and Their Characteristics**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Atmospheric concentration (ppm)</th>
<th>Annual concentration increase (%)</th>
<th>Relative greenhouse efficiency ($CO_2 = 1$)</th>
<th>Current greenhouse contribution (%)</th>
<th>Principal sources of gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>351</td>
<td>0.4</td>
<td>1</td>
<td>57</td>
<td>Fossil fuels, deforestation</td>
</tr>
<tr>
<td>CFCs</td>
<td>0.00225</td>
<td>5</td>
<td>15 000</td>
<td>25</td>
<td>Foams, aerosols, refrigerants, solvents</td>
</tr>
<tr>
<td>Methane</td>
<td>1.675</td>
<td>1</td>
<td>25</td>
<td>12</td>
<td>Wetlands, rice, livestock, fossil fuels</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>0.31</td>
<td>0.2</td>
<td>230</td>
<td>6</td>
<td>Fuels, fertilizer, deforestation</td>
</tr>
</tbody>
</table>

*Source: Flavin (1989).*

**CO₂**

Strong correlation between CO₂ concentrations and ΔT. (Antarctic ice cores)
Atmospheric CO₂ Concentration and Average Global Temperature over 160,000 Years

Figure 5.1
Recent History of Problem

From 1870 - 1990  \( \text{CO}_2 \) content or atmosphere has increased 25%

From 1870 - 1990  \( T \) has increased 0.5 - 0.7° C
Let’s calculate effect of CO$_2$ increase
in 1965 \([\text{CO}_2] = 320 \text{ ppm}\)
in 1990 \([\text{CO}_2] = 355 \text{ ppm}\)

Assume exponential growth
\[ C = C_0 e^{rt} \]
\[ 355 = 320 e^{r(1990-1965)} \]
\[ r = 0.41\% / \text{yr} \]

If this rate continues, we can calculate time to double CO$_2$
\[ 2 \times 280 = 355 e^{0.0041t} \]
\[ \uparrow \]
pre IR value
\[ t = 110 \text{ yr} \]
\[ \text{Date } = 1990 + 110 = 2100 \]
Effect on T
Doubling CO₂

1.5 - 4.5° C = ΔT

warmer than last 10,000 years

Best model (NRC)

\[ ΔT = ΔT_{\text{doub}} \times \ln \left( \frac{\text{CO}_2(t)}{\text{CO}_2(0)} \right) / \ln 2 \]

Controversy is what this means for future

Double CO₂ \( ΔT \sim 1.5 - 4.5° C \)
\[ \overset{\circ}{\overset{\circ}{O}} = \overset{\circ}{C} = \overset{\circ}{\overset{\circ}{O}} \]

Figure 3.4. Molecular responses to radiation.

- Shorter Wavelength → Longer
- UV → Visible → IR → Microwave
- Molecule dissociates
- Molecule vibrates
- Molecule rotates

CO₂ motions (vib.)

Figure 3.3. Infrared absorption by various compounds. The lines show the regions of the spectrum at which absorption occurs.

Greenhouse gases

\[
\begin{align*}
\text{CO}_2 & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \Quad
Global Carbon Cycle

FIGURE 3.5. Carbon cycle.
Carbon is exchanged between the atmosphere and the land and water reservoirs on Earth. The numbers give the approximate annual fluxes of carbon (in the form of CO₂) and the approximate amount stored in each reservoir in billions of metric tons. The existing cycles remove about as much carbon from the atmosphere as they add, but human activity is currently increasing atmospheric carbon by some 3 billion metric tons yearly. (The data are based on work by Bert Bolin of the University of Stockholm.)
Currently the cycle is out of balance. Humans release $6 - 7 \times 10^9$ tons of C to atmosphere / yr. (5 $\times 10^9$ tons due to fossil fuels. Deforestation $\sim 1 - 2 \times 10^9$ tons)

of the $6 - 7 \times 10^9$ excess tons / yr
$\sim 3 \times 10^9$ tons goes into atmosphere
(3 - 4 $\times 10^9$ tons $\rightarrow$ ocean + biosphere

Mathematics of Climate change

In estimating the “greenhouse effect” we assumed that the energy absorbed by the earth was equal to the energy radiated. Suppose they are not.

$Q_{\text{abs}} \neq Q_{\text{rad}}$

Suggest that

$Q_{\text{abs}} + \Delta Q_{\text{abs}} + \Delta F = Q_{\text{rad}} + \Delta Q_{\text{rad}}$

Effect:

$1 \times 10^9$ ton $\rightarrow 0.47$ ppm $CO_2$
\[ \Delta F = \Delta Q_{\text{abs}} - \Delta Q_{\text{rad}} \]
\[ \Delta T_s = \lambda \Delta F \]

\[ \text{climate sensitivity parameter} \]

Approx.

\[ Q_{\text{rad}} (\text{W/m}^2) = 1.83 T_s \, (^\circ \text{C}) + 209 \]

\[ 0.34 \leq \lambda \leq 1.03 \quad \lambda_{\text{av}} \sim 0.57 \]

**TABLE 8.3** Globally averaged radiative forcing due to changes in greenhouse gases, aerosols, and solar intensity from 1850 to the present

| Source: Based on IPCC, 1996. |

<table>
<thead>
<tr>
<th>Radiative forcing, ( \Delta F ) (W/m(^2))</th>
<th>Confidence level</th>
<th>Comments and uncertainty estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DIRECT GREENHOUSE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, CO(_2)</td>
<td>1.56</td>
<td>High</td>
</tr>
<tr>
<td>Methane, CH(_4)</td>
<td>0.47</td>
<td>High</td>
</tr>
<tr>
<td>Halocarbons</td>
<td>0.28</td>
<td>High</td>
</tr>
<tr>
<td>Nitrous oxide, N(_2)O</td>
<td>0.14</td>
<td>High</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.45</td>
<td>High</td>
</tr>
<tr>
<td><strong>INDIRECT GREENHOUSE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric ozone, O(_3)</td>
<td>-0.1</td>
<td>Low</td>
</tr>
<tr>
<td>Tropospheric ozone, O(_3)</td>
<td>0.4</td>
<td>Low</td>
</tr>
<tr>
<td><strong>DIRECT AEROSOLS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate SO(_4)</td>
<td>-0.4</td>
<td>Low</td>
</tr>
<tr>
<td>Fossil fuel soot</td>
<td>0.1</td>
<td>Very low</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>-0.2</td>
<td>Very low</td>
</tr>
<tr>
<td><strong>Total Direct</strong></td>
<td>-0.5</td>
<td>Range -0.2 to -0.8 W/m(^2)</td>
</tr>
<tr>
<td><strong>INDIRECT AEROSOLS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOLAR (since 1850)</td>
<td>0 to -1.5</td>
<td>Very low</td>
</tr>
<tr>
<td><strong>SUN</strong>:</td>
<td>0.3</td>
<td>Very low</td>
</tr>
</tbody>
</table>

**FIGURE 8.16** Direct radiative forcing due to changes in greenhouse gases from pre-industrial times to the present day as presented in Table 8.3. The total direct forcing is estimated to be 2.45 W/m\(^2\). The overall forcing of halocarbons is actually less than 11 percent when the indirect effects are included.
C emissions from fossil fuels

Syn fuels are terrible, coal is bad, nat. gas is better. However, as we said earlier, the biggest resource is coal.
Let’s make some models

\[ C \text{ emissions} = \text{Population} \times \frac{\text{GNP}}{\text{person}} \times \frac{\text{Energy}}{\text{GNP}} \times \frac{\text{C emissions}}{\text{energy}} \]

Assume exp. growth

\[ r = r_{\text{pop}} + r_{\text{GNP/pop}} + r_{\text{energy/GNP}} + r_{\text{emissions/energy}} \]

1.8% 1.5% -0.8% -0.2%

Base case \( \rightarrow \) (1.0) (1.2)
US Policy
April 21, 1993  US goal of return in 2000 to 1990 emission level is announced
Results to date:

Other greenhouse gases
CFCs   (Chlorofluorocarbons)
Principal component of ozone problem, as well.
Currently regulated by Montreal protocol that requires a 50% reduction (rel. to 1986) by 1998. BUT, because of long lifetime in atmosphere.
Methane (CH$_4$)

natural sources   decaying matter
“bovine flatulence”
termite farts

25 x more absorbing than CO$_2$

~1% / yr increase (correlated with population increase).
**N₂O (nitrous oxide)**
- fossil fuel burning
- fertilizer use
  + 0.2 % / yr

**Net Effect**

![Graph showing temperature increase over time](image)

**Figure 8.26** Equilibrium temperature increase (over preindustrial value) based on data given in Example 8.11.

**Aerosols**
- Provide “negative” forcing

![Diagram showing aerosol effects](image)

**Figure 8.23** Aerosols provide negative radiative forcing by reflecting sunlight and by enhancing cloud formation, which also increases reflection. Carbonaceous particles (soot) can provide negative forcing by absorbing sunlight. Aerosol absorption and reflection are direct effects; cloud formation and reflection is an indirect effect.
FIGURE 8.24 Changes in optical depth of the atmosphere following the El Chichon and Mount Pinatubo eruptions. (Source: IPCC, 1995)
Overall Net Effect

**Figure 8.25** Simulated global annual mean warming from 1860 to 1990 for greenhouse gases alone (dashed curve) and for greenhouse gases plus sulfate aerosols (solid curve) compared with measured values. (Source: IPCC, 1996)

**Figure 8.26** Global-mean radiative forcing, 1850-1990. The height of the rectangular bar represents a midrange estimate, while the error bars show an estimate of the uncertainty range. (Source: IPCC, 1996)
Connection with energy

Regional Effect of T increase

![Image](image.png)

**TABLE 8.10** TEMPERATURE INCREASES DUE TO EFFECTIVE DOUBLED CO₂ FOR VARIOUS CITIES

<table>
<thead>
<tr>
<th>City</th>
<th>ΔT (°F)</th>
<th>Days T &gt; 90°F</th>
<th>Growing season (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>July</td>
<td>Today</td>
</tr>
<tr>
<td>Washington</td>
<td>7.9</td>
<td>6.6</td>
<td>36</td>
</tr>
<tr>
<td>New York</td>
<td>7.9</td>
<td>6.7</td>
<td>15</td>
</tr>
<tr>
<td>Chicago</td>
<td>10.0</td>
<td>6.2</td>
<td>16</td>
</tr>
<tr>
<td>Omaha</td>
<td>10.4</td>
<td>6.2</td>
<td>37</td>
</tr>
<tr>
<td>Denver</td>
<td>11.7</td>
<td>6.1</td>
<td>33</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>9.3</td>
<td>7.5</td>
<td>5</td>
</tr>
<tr>
<td>Dallas</td>
<td>7.8</td>
<td>7.4</td>
<td>100</td>
</tr>
<tr>
<td>Memphis</td>
<td>8.5</td>
<td>6.7</td>
<td>65</td>
</tr>
</tbody>
</table>

Source: Hansen et al. (1986).

Profound effect on agriculture, water supply (no or reduced snowpack)

<table>
<thead>
<tr>
<th>Δh (sea)</th>
<th>Δt</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 10 - 20 cm</td>
<td>1900 - 2000</td>
</tr>
<tr>
<td>+ 10 - 20 cm</td>
<td>2025</td>
</tr>
<tr>
<td>+ 50 - 200 cm</td>
<td>2100</td>
</tr>
<tr>
<td>~ 6m</td>
<td>2300</td>
</tr>
</tbody>
</table>
Abatement of Greenhouse Warming
Estimated percentages of gross world product.

Costs and benefits of a vigorous program to control climate warming.

Benefits if damage from warming is high.

Benefits if damage from warming is moderate.

Costs.
Energy Use per Dollar of Output Declines Steadily Through 2015

Figure 5. Energy use per capita and per dollar of gross domestic product, 1970-2015 (index, 1970 = 1)

Carbon Emissions Continue To Grow Despite Stabilization Efforts

Figure 6. U.S. carbon emissions by sector and fuel, 1990-2015 (million metric tons)