Global Atmospheric Change

Updated IPCC report (2007)

- Optional reading
  - highlighted in 3rd edition of Masters
  - http://www.ipcc.ch/ipccreports/ar4-wg1.htm
  - The Scientific Basis
  - If you're interested, you can read the other reports too (mitigation, economic impacts, etc.)

Global Change

- Recent Proclamations
- Earth Atmospheric Structure
- Oxygen Isotopes
  - \(^{16}O\) and \(^{18}O\) vs. Temperature Record
- Global Temperature and Solar Effects
- Greenhouse Effect
  - Solar vs. Terrestrial Radiation
  - Greenhouse Gases

- Global Energy Balance
- Greenhouse Enhancement
  - Radiative Forcing
  - Climate Sensitivity
  - Greenhouse Gases vs. Temperature Record
  - Global Warming Potential
Background Quotes

- "The balance of evidence suggests a discernable human influence on global climate."
  —Committee of 2004 scientists involved in the Intergovernmental Panel on Climate Change, 1995

- "There is new and stronger evidence that most of the observed warming over the last 50 years is attributable to human activities."
  —Intergovernmental Panel on Climate Change, 2005, consensus of 2000 scientists

- "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"
  —Intergovernmental Panel on Climate Change, 2007, consensus of 2000 scientists

- "Be worried, be very worried"
  —Time, April 5, 2006

Overview of Earth's Atmosphere

- Mostly made up of nitrogen (78%) and oxygen (21%), followed by Argon (1%).
- Other gases present in small concentrations: carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), ozone (O₃), water vapor, CFCs (chlorofluorocarbons), NOₓ, SO₃, VOCs.

Human activities are much more likely to affect trace gas concentrations than [O₃] and [N₂]

- Layers of the atmosphere according to changes in temperature:
  → troposphere, stratosphere, mesosphere, thermosphere

- Atmosphere is well-mixed up to about 85-90 km altitude, then composition varies with altitude
Troposphere contains 90% of the mass of the atmosphere, and it is generally well mixed, with mixing time scales from a few minutes (vertical mixing in a thunder cloud) to a year (interhemispheric mixing).

The stratosphere is a stable layer, containing not quite 10% of the atmospheric mass.

**Global Temperature**

- In order to have a hope of predicting the future, we study the Earth's temperature in the past.
- Climatologists study tree rings, ice volume (i.e. markers of glaciation), fossil pollen, and oxygen isotopes to try and figure out the past temperature record.

**Oxygen Isotopes**

- Water evaporating from sea has H\textsubscript{2}18O and H\textsubscript{2}16O
  - H\textsubscript{2}18O is heavier, and it evaporates somewhat less readily.
  - This is called an “isotope effect”, and is very common in both physical and chemical processes—i.e. that the rate of a physical process or a chemical reaction will be slightly slower for a molecule containing the heavier isotope.

- The “heavy water” also precipitates very slightly faster than H\textsubscript{2}16O
- Precipitation that travels as far as the polar ice sheets is relatively more depleted in \(^{16}O\), leaving the sea enriched in \(^{18}O\)
- The more ice, the more the sea is enriched in \(^{18}O\) (particularly at the surface, where the critters are)
Sea creatures are enriched in $^{18}$O - equivalent to the level in ocean water. By measuring the $^{18}$O/$^{16}$O ratio, in the shells left by diatoms (and dating them with another stable isotope), we can find the temperature history of the Earth.

$$\delta^18O(\%) = \frac{\left(^{18}O/^{16}O\right)_{sample} - \left(^{18}O/^{16}O\right)_{reference}}{\left(^{18}O/^{16}O\right)_{reference}} \times 1000$$

Negative numbers—sample is “depleted” Positive numbers—sample is “enriched” Colder temperatures make the $^{18}$O $+$ or $-$ in the ocean? (Opposite in ice deposits)

$
^{18}$O in Ice Cores

- As world ice increases, $^{18}$O is selectively removed at the poles. In the same way, the global temperature can be derived from the ice in polar ice cores (up to 3 km long!).
- By examining air bubbles sealed in polar ice, the concentration of trace gases in the past can be determined, and a correlation between CO$_2$ concentrations and air temperature (per $^{18}$O) is seen
• In recent years, the temperature record is from instruments, carefully calibrated for technique, urban heat island effect, etc. (more later)
• Over the last million years, mid-latitude temperatures have oscillated between 9 and 16°C
• The fastest globally averaged temperature changes ever have been 1°C/century
• Right now we are looking at best guess climate change of 2°C by 2100, with a range of 1.4 to 5.8°C. Temperatures went up last century by 0.6°C

Global Temperature Change

• Tilt and orbit of the planet
  → These Milankovitch cycles change aspects of our orbit with 100000, 41000 and 23000 year periods.
  → There is a 10000 year cycle between glaciations, and the other cycles are observed as well, more or less. The sunlight only changes by 0.1%!

• Sunspot cycles
  → The sun has an 11-year cycle in the number of sunspots
  → More sunspots (which are cool) are associated with more faculae (which are brighter) results in -0.1 % more sunlight at the maximum of the cycle. Note the difference in effect of a long term 0.1% change and a short term one (2000–2001 was another solar maxima)
  • Shift in ocean and atmospheric circulation patterns

Greenhouse Effect

• To predict the extremely complex effect of changes in CO₂ concentrations researchers use general circulation models, but the starting point is a model that describes how radiation and the Earth interact.
• Recall: A blackbody absorbs all of the radiation that impinges upon it
• Energy is emitted from a blackbody according to its temperature (Stefan-Boltzmann Law)
Some of the incoming radiation is reflected off of the Earth's surface and it does not contribute to the Earth's warming (albedo).

From radiative equilibrium principles and Stefan-Boltzmann Law, we calculated a terrestrial radiative temperature of about 255 K.
Of the naturally occurring greenhouse gases, water vapor is the most important, absorbing strongly below 8 and above 18 μm.

Carbon dioxide is next, with a strong band centered at 15 μm.

Between 7 and 12 μm there is relatively clear sky for outgoing radiation—the bump in the middle is from ozone.
Energy balance includes non-radiation energy transfer

Incoming solar radiation (average for the Earth’s surface)

\[
\frac{1370 \, \text{W}}{4} = 342 \, \text{W/m}^2
\]

The albedo reflects back 31% of this energy:

\[
\frac{342 \, \text{W/m}^2 \times 0.31}{10} = 107 \, \text{W/m}^2
\]

Leaving 235 W/m² to be absorbed.

If the temperature isn’t changing, then the same amount of energy, 235 W/m² needs to leave the Earth.

But we know that some of the energy is absorbed by the atmosphere, so in order to balance the equation, the Earth needs to radiate more to get the necessary amount of energy out. → The Earth needs to be hotter.

The Earth’s average temperature is 288K:

Energy radiated by the Earth:

\[
\sigma T^4 = 5.67 \times 10^{-8} \, \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4} (288 \, \text{K})^4 = 390 \, \text{W/m}^2
\]

Of that 390 W/m², only 40 passes through the atmosphere, mostly through the little window between 7 and 12 μm.

Thermals and latent heat transfer another 102 W/m² to the atmosphere.

The atmosphere absorbs all of this heat, and then radiates the energy, sending another 195 W/m² out of the atmosphere and 324 back to the surface.

Rate of energy gain = Rate of energy loss

Earth’s surface: 168 + 324 + 30 + 78 + 24 + 30 + 390
Atmosphere: 67 + 78 + 24 + 350 + 165 + 30 + 324
Space: 107 + 165 + 30 + 40 = 342

(All units W/m²)

Incoming
168 + 30 from Sun + 324 from Atmos.
Outgoing
78 Evapotranspiration + 24 thermals + 30 reflected solar + 390 terrestrial blackbody radiation
Enhancement of Greenhouse Effect

If the system is perturbed by adding radiative forcing, \( F \) (W/m²), then the former equation, 
\[ Q_{\text{abs}} = Q_{\text{rad}} \]
becomes (at a new equilibrium):
\[ Q_{\text{abs}} + \Delta Q_{\text{abs}} + \Delta F = Q_{\text{abs}} + \Delta Q_{\text{abs}} + \Delta Q_{\text{rad}} \]
\[ \Delta F = \Delta Q_{\text{rad}} - \Delta Q_{\text{abs}} \]
\( \Delta F \) from changes in:
- Greenhouse gas concentrations
- Aerosols
- Albedo
- Solar constant

Climate Sensitivity

Climate sensitivity parameter
\[ \Delta T_s = \lambda \Delta F \]
\( \lambda \) = the climate sensitivity parameter
\( T_s \) = surface temperature (K)
\( \Delta F \) = forcing in W/m²
\[ \lambda = \frac{\Delta T_s}{\Delta F} = \frac{\Delta T_s}{\Delta Q_{\text{rad}} - \Delta Q_{\text{abs}}} = \left( \frac{\Delta Q_{\text{rad}} - \Delta Q_{\text{abs}}}{\Delta T_s} \right)^{-1} \]

Which can also be written in incremental form (\( \Delta T, \) etc.).

- Climate sensitivity depends on:
  - How much the outgoing radiation at the top of the atmosphere changes (\( \Delta Q_{\text{rad}} / \Delta T_s \)) as the surface temperature changes, and
  - The change of incoming energy that is absorbed as the surface temperature changes (\( \Delta Q_{\text{abs}} / \Delta T_s \)).

- Using infrared satellite data, an empirical relationship between the outgoing radiation and \( T_s \) has been derived.

\[ Q_{\text{rad}} = 1.83T_s + 209 \]

Example

Doubling the [CO₂] causes a radiative forcing of 4.35 W/m². Assuming that the Earth's albedo doesn't change (it probably will), estimate the climate sensitivity factor \( \lambda \) and use it to estimate the eventual change in the surface temperature of the Earth needed to balance incoming and outgoing radiation.

Solve:
\[ Q_{\text{rad}} = 1.83T_s + 209 \]
for an incremental change in \( Q \) and \( T \).
To get the change of $T$ with $Q$ we just need the slope of this equation,

$$\frac{\Delta Q_{alb}}{\Delta T} = 1.83$$

Since we are assuming the albedo doesn’t change,

$$\frac{\Delta Q_{alb}}{\Delta T} = 0$$

So this approximation of the climate sensitivity factor is:

$$\lambda = \left( \frac{\Delta Q_{alb}}{\Delta T} - \frac{\Delta Q_{alb}}{\Delta T} \right)^{-1} = 1.83^{-1} = 0.55 \frac{°C}{W/m^2}$$

If doubling CO$_2$ creates a radiative forcing of 4.35 W/m$^2$, then

$$\Delta T = \lambda \Delta F = 0.55 \frac{°C}{W/m^2} \times 4.35 \frac{W}{m^2} = 2.4°C$$

The climate sensitivity factor, $\lambda$, is quite uncertain. The IPCC 1995 estimates are from 0.34 to 1.03, with the best guess of 0.57.

Tom, M. and J. Harte, Geophysical Research Letters, May 26, 2006:

“We quantified this feedback for CO$_2$ and CH$_4$ by combining the mathematics of feedback with empirical ice-core information and general circulation model (GCM) climate sensitivity, finding that the warming of 1.5–4.5°C associated with anthropogenic doubling of CO$_2$ is amplified to 1.6–6.0°C warming, with the uncertainty range deriving from GCM simulations and paleo temperature records. Thus, anthropogenic emissions reach higher total GHG concentrations, and therefore more warming, than would be predicted in the absence of this feedback.”

Scheffer, M., V. Brovkin, and P.M. Cox, Geophysical Research Letters, May 26, 2006:

“…we suggest that the feedback of global temperature on atmospheric CO$_2$ will promote warming by an extra 15–78% on a century-scale. This estimate may be conservative as we did not account for synergistic effects of likely temperature-mediated increase in other greenhouse gases.”

Positive forcings warm the Earth, negative forcings cool the Earth

**Fig. 6.29**
Figure SPM.2. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and other important agents and mechanisms, together with the corresponding geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are shown. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional net radiative forcing but are not included here. Figure 2.20 shows the probability density functions for other possible effects of methane on climate change (J.K. Figure 2.20).

Gases

Aerosols: Sulfate, fossil fuel soot, biomass burning (direct increase or decrease in absorption or reflection of sunlight) and indirect: aerosol induced changes in cloud formation.

Arhenius is credited with making the first calculations of the effect of CO₂ on the Earth's temperature.
Sources of CO₂

- Burning fossil fuels
  - That carbon was removed from the carbon cycle millions of years ago
- Deforestation
  - Often referred to as biomass burning, but the key point is that the total amount of CO₂ stored in the biosphere is reduced because there is less net carbon stored in living things
- Cement production

Biofuels do not contribute to increasing CO₂ in the atmosphere unless they are associated with deforestation.

CO₂ emissions: 1958-2000 = 201 GtC

- 55% of carbon emitted remains in the atmosphere
- Rest goes to either:
  - oceans
  - terrestrial biosphere (trees and plants)
  - soils
Human Release of Carbon

The numbers in the boxes are the amount of carbon in that reservoir, in gigatons (10^9 tonnes or 10^15 kg).

Anthropogenic emissions are ~5.5 Gt/yr from fossil fuels and a little cement, ~1.6 Gt/yr from deforestation in the tropics.

This is offset by about 2 Gt/yr uptake into the oceans, 0.5 Gt/year re-growth of Northern Forests, and 1.3 Gt/yr other sinks—increased plant growth from nitrogen and CO2 fertilization.

Net storage in the atmosphere:

The airborne fraction is to a degree a function of the rate of emissions. If the same net emissions are added over a longer time period, the ocean and plants have more time to absorb the carbon, and the airborne fraction is lower; possibly 35%.
Methane has more than doubled since pre-industrial times.

CH₄ + OH + O₃ → HO⁺ + H⁺ + HO₂
HO₂ + OH → HO₂⁺ + HO₂

Net reduction of [OH] after reaction with methane
- Results in increased [CH₄]
- Global warming could free large amounts of methane from permafrost and provide another positive feedback loop.
- A large enough temperature increase may cause CH₄ release from methane clathrates in the ocean

Nitrous Oxide (N₂O)
N₂O is produced in nitrification reactions—either by bacteria or in fertilizer production:

NH₄⁺ → N₂ + N₂O → NO → NO₂ → NO₃
Figure TS.1

Variations of deuterium (D) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods. (Adapted from Figure 6.3)

- Aerosols can backscatter sunlight
  - Increases albedo, causes cooling
- Aerosols may cloud condensation nuclei
  - Increases cloud reflectivity, thereby having a cooling effect. This is the indirect effect of aerosols.
- The effect of aerosols has been investigated with natural experiments such as the eruption of Mt. Pinatubo.
- Real aerosol effects poorly understood

<table>
<thead>
<tr>
<th>TABLE 4.4</th>
<th>Examples of halocarbons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>Designation</td>
</tr>
<tr>
<td>CO₂</td>
<td>CO₂</td>
</tr>
<tr>
<td>CH₄</td>
<td>CH₄</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
</tr>
</tbody>
</table>

Source: IPCC 1990
Global Warming Potential

- Gases contribute to the greenhouse effect if they absorb in the 7-12 µm window where natural greenhouse gasses have not already saturated the bands.
- If an absorber only adds to the “wings” of an absorption band, and most of the band is already saturated, then it will not be so effective on a per-molecule basis.
- Its greenhouse warming potential (GWP) will be proportional to the square root of its concentration (CH4, N2O) or the log of its concentration (CO2).
- If it absorbs in a clear window, then the effect of the full strength of the absorption band will be felt, its will be linearly related to its concentration. Saturation is generally less than 10% of the band.
- Completely anthropogenic gases fall in this category, including most CFC’s.

For the 3 regimes, we have:

- linear: \[ F = k_1(C - C_0) \]
- squareroot: \[ F = k_2(\sqrt{C} - \sqrt{C_0}) \]
- logarithmic: \[ F = k_3(\ln C - \ln C_0) \]

The \( k \)'s are derived from the absorption spectra and the overall atmospheric absorption for each particular gas. \( k_{CO_2} = 6.3 \).
<table>
<thead>
<tr>
<th>Chemical Species</th>
<th>Traditional</th>
<th>21yr</th>
<th>50yr</th>
<th>100yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>17</td>
<td>22</td>
<td>29</td>
<td>44</td>
</tr>
<tr>
<td>Chlorofluorocarbons (CFCs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFC-11</td>
<td>22</td>
<td>60</td>
<td>1,000</td>
<td>2,000</td>
</tr>
<tr>
<td>CFC-12</td>
<td>22</td>
<td>60</td>
<td>1,000</td>
<td>2,000</td>
</tr>
<tr>
<td>CFC-113</td>
<td>22</td>
<td>60</td>
<td>1,000</td>
<td>2,000</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>HFC-134b</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>HFC-135a</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>Hydrofluorocarbons (HFCs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-152a</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>HFC-152b</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>HFC-153a</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>HFC-154a</td>
<td>1</td>
<td>4,000</td>
<td>9,500</td>
<td>19,000</td>
</tr>
<tr>
<td>Perfluorocarbons (PFCs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFC-113</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-114</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-115</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-116</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-117</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-118</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-119</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-120</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
<tr>
<td>PFC-121</td>
<td>1,500</td>
<td>3,500</td>
<td>5,000</td>
<td>6,500</td>
</tr>
</tbody>
</table>