Global Climate Change

Greenhouse Gases and Earth’s Energy Balance

![Graph showing CO₂ in air over years from 1960 to 2010]
Outline of Topics

1. The Natural Earth System
   - Earth’s Energy Balance
   - The Greenhouse Effect

2. Radiative Forcing
   - The Carbon Cycle
   - Other GHGs
   - Energy Balance Effects

3. Climate Change
   - Temperature
   - Models and Predictions
To maintain balance, Earth must also emit at the same rate of $1.7 \times 10^{17}$ J/s.

Divide by surface area: 342 W/m$^2$.

The solar constant, a long-term annual average.
Lecture Question

How much of this sunlight is (a) reflected immediately, (b) absorbed by the atmosphere, or (c) absorbed by Earth’s surface?

- 30% reflected back to space
- 25% absorbed by atmosphere (see figure)
- 45% absorbed by surface land and water
Earth’s Energy Balance: Blackbody Radiation

Contrast Earth’s incoming and outgoing radiation.

- The sun and the earth are reasonable blackbody radiators
- Blackbody radiator: light emitted is determined almost entirely by temperature of the radiator
- See figure: hotter sun emits 10% uv, 40% vis, 50% near-IR, while Earth emits entirely in the mid-IR at 5–50 µm.
Lecture Question
What is the greenhouse effect?

- 90% of IR light emitted by the surface/clouds is re-absorbed by GHGs
- GHGs re-emit some IR light back to the surface
The Greenhouse Effect

Is there direct evidence of the greenhouse effect?

- 90% (avg) emitted light is absorbed and re-emitted
- But some light escapes without heating air through an IR Window
- IR window is dynamic, depends on composition (esp water vapor)
- main window is 8–14 µm
- more windows in 0.2–5.5 µm
What are greenhouse gases, GHGs? Name the five most important GHGs present naturally in the atmosphere.

Greenhouse gases are those that absorb in the region, 5–50 µm, emitted by the earth’s surface. The most important natural GHGs are:

- water, H₂O
- carbon dioxide, CO₂
- ozone, O₃
- methane, CH₄
- nitrous oxide, N₂O
The Greenhouse Effect

Give a more detailed description of Earth’s current energy balance.

Incoming solar radiation: 340.4

Total reflected solar radiation: 99.9

Absorbed by atmosphere: 77.1

Reflected by clouds & atmosphere: 77.0

Reflected by surface: 22.9

Total outgoing infrared radiation: 239.9

Emitted by atmosphere: 169.9

Emitted by clouds: 29.9

Absorbed by surface: 163.3

Net absorbed: 0.6

Greenhouse gases

Atmospheric window: 40.1

Latent heat (change of state)

Thermals (conduction/convection)

Evapotranspiration

18.4

86.4

Global Climate Change

The Natural Earth System
The Greenhouse Effect

Compare the heat inputs of the atmosphere and surface.

The atmosphere receives: 540 W/m²:
- sunlight (14%)
- ‘thermals’ (3%)
- latent heat (16%)
- absorption of IR light by GHGs (66%)

The surface receives: 504 W/m²:
- sunlight (32%)
- re-emitted IR light from GHGs (68%). *This is the greenhouse effect.*
The Global Carbon Cycle

What is a Keeling Curve? Explain the trends and fluctuations.

- Regular oscillations, with 1-yr period
- NH and SH 180° out of phase
- Oscillation amplitude greater at ML
- General increase in CO₂
- ML increasing faster than SP
What is a **biogeochemical cycle**?

- A biogeochemical cycle is a description of the major reservoirs of a substance, and the processes that exchange that substance between the reservoirs.
- Each reservoir has a *stock* of substance in it, and each exchange process causes a *flow* of substance from one reservoir to another.
- Processes are biological/chemical/geological, and can operate on greatly different time scales.
- Biogeochemical cycles can be local or global.
Lecture Question

Describe the carbon cycle and how we have affected it.
The Global Carbon Cycle: Fast and Slow Carbon Pools

Explain the difference between ‘fast’ and ‘slow’ carbon cycles.

Diagram showing the different carbon pools and their time required to affect the atmosphere in years.
The ‘old’ carbon we emit re-distributes between the three ‘fast’ pools

- Uptake by dissolution into surface ocean and by fast-growing plans is pretty rapid (avg 4.5 yr)

- But most of this is re-emitted back into the atmosphere (still in ‘fast’ C pool)
### The Global Carbon Cycle

#### How about some numbers this time?

<table>
<thead>
<tr>
<th>Anthropogenic sources</th>
<th>fossil fuel combustion, cement production</th>
<th>$8.3 \pm 0.4$ PgC/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>changes in land-use</td>
<td></td>
<td>$1.0 \pm 0.5$ PgC/yr</td>
</tr>
<tr>
<td><strong>total emissions</strong></td>
<td></td>
<td><strong>$9.3 \pm 0.6$ PgC/yr</strong></td>
</tr>
<tr>
<td>Partitioning among reservoirs</td>
<td>net ocean uptake</td>
<td>$2.5 \pm 0.5$ PgC/yr</td>
</tr>
<tr>
<td></td>
<td>net land uptake</td>
<td>$2.6 \pm 0.8$ PgC/yr</td>
</tr>
<tr>
<td></td>
<td><strong>net storage in atmosphere</strong> <em>(measured)</em></td>
<td><strong>$4.3 \pm 0.1$ PgC/yr</strong></td>
</tr>
</tbody>
</table>

- Less than half (46%) of emitted carbon stays in air
- Dissolution in ocean causes acidification: $\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$
- Land sink has the highest uncertainty, subject of much current research
Lecture Questions

How much has atmospheric CO$_2$ increased since 1750?
What is the recovery time if all anthropogenic CO$_2$ emissions ceased?

- CO$_2$: 280 → 400 ppm (and rising)
- We have emitted 555 GtC to date
- Figure shows predicted recovery after CO$_2$ ‘pulse’

IPCC: ‘Depending on the [future emission] scenario, 15 to 40% of emitted CO$_2$ will remain in the atmosphere longer than 1000 years.’
### Lecture Question

What GHGs have increased since 1750?

<table>
<thead>
<tr>
<th>GHG</th>
<th>1750</th>
<th>Recent</th>
<th>GWP</th>
<th>Lifetime, yr</th>
<th>RF, W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>280 ppm</td>
<td>400 ppm</td>
<td>1</td>
<td>100-300</td>
<td>1.68</td>
</tr>
<tr>
<td>CH₄</td>
<td>722 ppb</td>
<td>1825 ppb</td>
<td>28</td>
<td>12</td>
<td>0.97</td>
</tr>
<tr>
<td>N₂O</td>
<td>270 ppb</td>
<td>325 ppb</td>
<td>265</td>
<td>121</td>
<td>0.17</td>
</tr>
<tr>
<td>O₃</td>
<td>237 ppb</td>
<td>337 ppb</td>
<td>n/a</td>
<td>short</td>
<td>*</td>
</tr>
<tr>
<td>CFC-11</td>
<td>0</td>
<td>235 pptr</td>
<td>4,660</td>
<td>45</td>
<td>0.18 (all)</td>
</tr>
<tr>
<td>CFC-12</td>
<td>0</td>
<td>527 pptr</td>
<td>10,200</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>CFC-113</td>
<td>0</td>
<td>74 pptr</td>
<td>5,820</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>HCFC-22</td>
<td>0</td>
<td>220 pptr</td>
<td>1,760</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>

- GWP is the *global warming potential* relative to CO₂ over a 100 yr period
- Lifetime is for the troposphere; it is not well defined for CO₂
- There are a number of other halogenated compounds not included in the table: HCFCs, HFCs, halons, CCl₄, SF₆
The Methane Cycle

What human activities have lead to the increase in CH$_4$?

- Biomass burning: 35 Tg/yr
- Fossil fuels: 96 Tg/yr
- Landfills & waste: 75 Tg/yr
- Rice cultivation: 36 Tg/yr
- Livestock: 89 Tg/yr

- Note unit change compared to CO$_2$ emissions
- Total anthropogenic flux: 330 Tg/yr (50–65% of total flux from all sources)
- Main natural source: wetlands (about 200 Tg/yr)
What human activities have lead to the increase in N$_2$O?

- Atmospheric deposition: 0.6 Tg/yr
- Rivers estuaries: 0.6 Tg/yr
- Human waste: 0.2 Tg/yr
- Biomass burning: 0.7 Tg/yr
- Agriculture: 4.1 Tg/yr
- Fossil fuels: 0.7 Tg/yr

- Current anthropogenic flux: 7 Tg/yr (35–40% of total from all sources)
- Main natural sources: soils (6.6 Tg/yr) and oceans (3.8 Tg/yr)
Lecture Question

What is radiative forcing?

2nd panel adds an atmosphere with GHGs (some flows omitted)

3rd panel shows an imbalance of 4 W/m² due to a doubling of CO₂ concentration

Radiative forcing, RF, is this quantitative measure of the radiative energy imbalance

\[ RF = \text{incoming} - \text{outgoing} \]

4th panel shows a restored energy balance after global warming has occurred
What factors are currently causing radiative forcing?

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂ H₂Ostr O₃ CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃ CFCs HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂ CH₄ O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂ CH₄ O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate CH₄ O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust Sulphate Nitrate Organic carbon Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Cloud adjustments due to aerosols</td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td>Albedo change due to land use</td>
<td></td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
<tr>
<td>Total anthropogenic RF relative to 1750</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>2.29 [1.13 to 3.33]</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>1.25 [0.64 to 1.86]</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td>0.57 [0.29 to 0.85]</td>
<td>M</td>
<td></td>
</tr>
</tbody>
</table>

Radiative forcing relative to 1750 (W m⁻²)
**Lecture Question**

**What are the recent temperature trends?**

- Figures show combined land & surface temps
- 1880–2012: 0.85 °C increase
- Since 1951: rate of increase is 0.12 °C per decade
- 2014 recently declared hottest year ever measured directly (and no El Niño)
Besides the increase in global mean temperature, what other changes have been observed?

- Oceans absorbed most (90+%) of the heat dumped into the system in the last 40 yr
- Precipitation has increased (NH mid-latitude)
- Extreme events: heat waves, droughts, heavy precipitation events
- Glaciars have shrunk worldwide
- Antarctic and Greenland ice sheets have lost mass for two decades
- Arctic ice sheet and NH snow cover (see figure)
- Sea levels have risen by 0.19 m since 1901 (figure)
- Non-climate: ocean pH has decreased by 0.11 (30% increase in $[H_3O^+]$)
Climate Modeling

What are General Circulation Models (GCMs)?

- Math model of the circulation of air or ocean to describe/simulate climate
- Divides fluid up into 3-d grid
- Mathematically describes flow of energy and mass between grids using set of differential equations solved numerically
- Complete climate model requires coupled air/ocean GCMs plus other components (e.g., ice sheet model)
Can we attribute temperature increases to human activities?

Separating Human and Natural Influences on Climate

- Observations
- Natural and Human Factors
- Natural Factors Only

Global Temperature Change (°F)

Year

1900 1920 1940 1960 1980 2000

-1.0 -0.5 0.0 0.5 1.0 1.5 2.0
Response to a change that either opposes further change (negative feedback) or amplifies it (positive feedback).

Can lead to non-linear equations that are harder to model.

Possible carbon cycle feedbacks:
- $\text{CO}_2$ solubility decreases with increasing temperature (positive)
- carbon fertilization effect (negative)
- increased rate of decomposition with temperature (positive)
- melting of permafrost releases stored methane (positive)

Hydrologic cycle feedback: water vapor pressure increases with temperature (positive)

Earth’s albedo:
- increases due to increased cloud cover (negative)
- decreases due to reduced snow/ice cover (positive)

Changes in air/ocean circulation causes local feedback effects
Lecture Question
How does the IPCC use models to predict future climate effects?

- Range of values due to variability in models (scientific uncertainty)
- Range of values due to variability in emission scenario (policy response uncertainty)
- Two sources of variability roughly similar
• A lower warming target, or a higher likelihood of remaining below a specific warming target, will require lower cumulative CO₂ emissions. Accounting for warming effects of increases in non-CO₂ greenhouse gases, reductions in aerosols, or the release of greenhouse gases from permafrost will also lower the cumulative CO₂ emissions for a specific warming target (see Figure SPM.10). {12.5}

• A large fraction of anthropogenic climate change resulting from CO₂ emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO₂ from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO₂ emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO₂ will remain in the atmosphere longer than 1,000 years. {Box 6.1, 12.4, 12.5}

• It is virtually certain that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for many centuries. The few available model results that go beyond 2100 indicate global mean sea level rise above the pre-industrial level by 2300 to be less than 1 m for a radiative forcing that corresponds to CO₂ concentrations that peak and decline and remain below 500 ppm, as in the scenario RCP2.6. For a radiative forcing that corresponds to a CO₂ concentration that is above 700 ppm but below 1500 ppm, as in the scenario RCP8.5, the projected rise is 1 m to more than 3 m (medium confidence). {13.5}

Projected warming is a function of cumulative emissions
555 GtC emitted to date
RCP = Representative Concentration Pathway
Number is projected forcing in 2100 relative to 1750

Global Climate Change
## Lecture Question

**What changes are predicted for temperature and sea level?**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2046–2065</th>
<th></th>
<th>2081–2100</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Likely range</td>
<td>Mean</td>
<td>Likely range</td>
</tr>
<tr>
<td><strong>Global Mean Surface Temperature Change (°C)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP2.6</td>
<td>1.0</td>
<td>0.4 to 1.6</td>
<td>1.0</td>
<td>0.3 to 1.7</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>1.4</td>
<td>0.9 to 2.0</td>
<td>1.8</td>
<td>1.1 to 2.6</td>
</tr>
<tr>
<td>RCP6.0</td>
<td>1.3</td>
<td>0.8 to 1.8</td>
<td>2.2</td>
<td>1.4 to 3.1</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>2.0</td>
<td>1.4 to 2.6</td>
<td>3.7</td>
<td>2.6 to 4.8</td>
</tr>
<tr>
<td><strong>Global Mean Sea Level Rise (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP2.6</td>
<td>0.24</td>
<td>0.17 to 0.32</td>
<td>0.40</td>
<td>0.26 to 0.55</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.26</td>
<td>0.19 to 0.33</td>
<td>0.47</td>
<td>0.32 to 0.63</td>
</tr>
<tr>
<td>RCP6.0</td>
<td>0.25</td>
<td>0.18 to 0.32</td>
<td>0.48</td>
<td>0.33 to 0.63</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.30</td>
<td>0.22 to 0.38</td>
<td>0.63</td>
<td>0.45 to 0.82</td>
</tr>
</tbody>
</table>

- Ranges are 90% confidence intervals