Science of climate change: the atmosphere

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Observed climate change
$\text{CO}_2$ concentration, surface temperatures, land glaciers, precipitation

Mechanisms of climate change
Earth’s energy balance, radiative transfer, atmospheric composition, feedbacks

Climate change projections
Temperature, hydrological cycle, extreme events
Observed climate change
CO$_2$ concentration, surface temperatures, land glaciers, precipitation

Mechanisms of climate change
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Climate change projections
Temperature, hydrological cycle, extreme events
Carbon dioxide concentration has risen from 280 ppmv to 410 ppmv.

Keeling et al. (2001, updated), Etheridge et al. (1998)
Global mean surface temperatures have risen by about 1 K
The warming is global but inhomogeneous
Land glaciers are retreating

Royal Geographical Society, GlacierWorks
Land glaciers are retreating
Precipitation in midlatitudes has increased but trends are relatively uncertain.
Observed climate change
$\text{CO}_2$ concentration, surface temperatures, land glaciers, precipitation

**Mechanisms of climate change**
Earth’s energy balance, radiative transfer, atmospheric composition, feedbacks

Climate change projections
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Atmospheric absorption and emission of infrared radiation cause a greenhouse effect.

Joseph Fourier (1824)
Atmospheric absorption and emission of infrared radiation cause a greenhouse effect

incoming solar radiation

outgoing infrared radiation

earth

atmosphere

Joseph Fourier (1824)
The greenhouse effect is caused by trace amounts of water vapor and carbon dioxide.
Water vapor and carbon dioxide interact with infrared radiation

H₂O:

CO₂:
Without the greenhouse effect, the earth’s temperature would be 255 K (−18°C)

Radiative equilibrium:

\[(1 - \alpha)S = \sigma T_s^4\]

\(S\) – incoming solar radiation, \(\alpha\) – albedo, 
\(\sigma\) – Stefan–Boltzmann constant, \(T_s\) – surface temperature
The earth’s surface receives twice as much energy from the atmosphere as from the sun.

Radiative equilibrium:

**surface:** \( (1 - \alpha)S + \varepsilon \sigma T_a^4 = \sigma T_s^4 \)

**atmosphere:** \( \varepsilon \sigma T_s^4 = 2\varepsilon \sigma T_a^4 \)

\( S \) – incoming solar radiation, \( \alpha \) – albedo, \( \varepsilon \) – infrared emissivity, \( \sigma \) – Stefan–Boltzmann constant, \( T_s \) – surface temperature, \( T_a \) – atmospheric temperature

*Svante Arrhenius (1896)*
Carbon emissions change the earth’s temperature

Increasing CO$_2$ concentration increases the infrared emissivity $\varepsilon$ and warms the earth’s surface and atmosphere.

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When snow and ice melt, more sunlight is absorbed, further warming the earth. This is the ice albedo feedback.

Svante Arrhenius (1896)
Refined spectroscopy and multi-layer radiative transfer give a climate sensitivity of 2 K.

Assuming fixed relative humidity, i.e. allowing for the water vapor feedback, gives a warming of 2 K per doubling of CO$_2$.

*Manabe and Wetherald (1967)*
General circulation climate models provide a best estimate of expected climate change.

GCMs integrate the radiative–convective dynamics with the large-scale fluid dynamics of the atmosphere and ocean.

They add detail to the simpler single-column models, giving climate sensitivities of 1.5–4.5 K.

*Manabe and Wetherald (1975), Hansen et al. (1984), and many more since then*
Other anthropogenic activity forces climate change

<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>1.88 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, 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></td>
<td>Albedo change due to land use</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>
</tbody>
</table>

### Total anthropogenic RF relative to 1750

- **2011**: 2.29 [1.13 to 3.33] (H)
- **1980**: 1.25 [0.64 to 1.86] (H)
- **1950**: 0.57 [0.29 to 0.85] (M)

**Radiative forcing relative to 1750 (W m⁻²)**
Methane and its decay products contribute a large fraction of the greenhouse forcing.

Methane is released by a variety of anthropogenic sources, the single largest being enteric fermentation globally (natural gas and petroleum systems in the US).

The lifetime of methane in the atmosphere is about a decade, much less than that of carbon dioxide.

*Dlugokencky et al. (1994, updated), MacFarling Meure et al. (2006)*
Aerosols can both warm and cool the planet.

Aerosols scatter some solar radiation back to space (cooling) but also absorb some (warming). Aerosols also affect the nucleation of cloud droplets, changing the radiative properties and life cycle of clouds.
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Surface temperatures are projected to rise.
Dry regions get drier, wet regions get wetter

change in precipitation minus evaporation

High-intensity hurricanes become more frequent and have substantially higher precipitation.

Hurricane Harvey
(107 deaths, $125 billion damage)

Kerry Emanuel (2017)
Cloud feedbacks remain a major source of uncertainty

Cloud feedbacks are the main reason we have a range of climate sensitivity 1.5–4.5 K.
Carbon dioxide concentration has increased by nearly 50%, the global mean surface temperature has risen by about 1 K, land glaciers have retreated.

The basic mechanism of global warming is well-understood: increased CO₂ enhances the greenhouse effect, the warming is amplified by the water vapor feedback.

General circulation models provide best estimate of change: warming is largest on land and in the Arctic, hydrological cycle is amplified, extreme events become more frequent.