Earth’s Climate from Space

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Earth’s energy balance in space

There is a balance between the absorbed sunlight and the thermal radiative cooling of the planet.

Without the greenhouse effect, this balance would occur at a frigid global temperature of \(-18^\circ\text{C}\).

\[
\frac{S}{4} (1 - \alpha) = F
\]

- Fourier (1824); Tyndall (1858); Arhenius (1896); Lacis et al. (2011)
Earth’s global average energy balance: no atmosphere

Surface Temperature = 255 K = \(-18^\circ C\)

\[
\frac{S}{4} (1 - \alpha) = F \sim \varepsilon \sigma T_s^4
\]

\begin{align*}
S &\approx 1361 \text{ Wm}^{-2} \\
\alpha &\approx 0.3 \\
\varepsilon & = 1 \\
\sigma & = 5.67 \times 10^{-8} \text{ Wm}^{-2}K^{-4}
\end{align*}
Earth’s global average energy balance: add atmosphere

Solar > Thermal

\[ S = 4 \left(1 - \alpha \right) = F \sim \varepsilon \sigma T_s^4 \]

\[ S \approx 1361 \text{ Wm}^{-2} \quad \alpha \approx 0.3 \quad \varepsilon < 1 \quad \sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}K^{-4} \]
Earth’s global average energy balance: present day

Solar
240 Wm$^{-2}$

Surface Temperature = 288 K = +15°C

Thermal
240 Wm$^{-2}$

390 Wm$^{-2}$

Efficiency ~60%

$S/4 (1 - \alpha) = F \sim \varepsilon \sigma T_s^4$

$S \approx 1361$ Wm$^{-2}$  $\alpha \approx 0.3$  $\varepsilon \approx 0.6$  $\sigma = 5.67 \times 10^{-8}$ Wm$^{-2}$K$^{-4}$
Earth’s Global Annual Average Energy Balance

Mars

Incoming Solar radiation (shortwave) 148 W m⁻² (340 Wm⁻²)

Total shortwave reflected to space 38 W m⁻² (100 Wm⁻²)

Absorbed by atmosphere 14 W m⁻²

Reflected by surface to space 29 W m⁻² (185 Wm⁻²)

Shortwave flux to surface 125 W m⁻²

Outgoing Infrared radiation (longwave) 110 W m⁻² (240 Wm⁻²)

Emitted by atmosphere to space 33 W m⁻²

Absorbed by atmosphere 342 W m⁻² (342 Wm⁻²)

Longwave emitted by atmosphere to surface 29 W m⁻² (342 Wm⁻²)

Reflected by surface to space 2 W m⁻² (2 Wm⁻²)

P. L. Read (Univ Oxford) after Angelats i Col et al. (2005)
Venus

P. L. Read (Univ Oxford) after Mendonca (2013)
Top of Atmosphere Radiative Energy Fluxes
CERES/TERRA, September 2004

Net Radiation (Wm$^{-2}$)
The Net Radiation Balance

Why don’t the tropics get warmer and warmer and the poles colder and colder?
The global circulation
## Comparing the planets

...thanks to Wikipedea

<table>
<thead>
<tr>
<th>Planet</th>
<th>Surface Temp.</th>
<th>Surface pressure</th>
<th>Diameter (Earth’s)</th>
<th>Rotation (hrs)</th>
<th>Coriolis Effect</th>
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<tbody>
<tr>
<td>Mercury</td>
<td>80-700 K</td>
<td>~0</td>
<td>0.38</td>
<td>~0</td>
<td>None</td>
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<tr>
<td>Venus</td>
<td>737 K</td>
<td>200 kPa</td>
<td>0.95</td>
<td>slow</td>
<td>Weak</td>
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<td>Earth</td>
<td>184-330 K</td>
<td>101 kPa</td>
<td>1</td>
<td>24</td>
<td>Moderate</td>
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<tr>
<td>Mars</td>
<td>130-308 K</td>
<td>0.6 kPa</td>
<td>0.53</td>
<td>24.5</td>
<td>^Small</td>
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<tr>
<td>Jupiter</td>
<td>*165 K</td>
<td>20-200 kPa</td>
<td>11.2</td>
<td>9.8</td>
<td>STRONG</td>
</tr>
<tr>
<td>Saturn</td>
<td>*134 K</td>
<td>1000 kPa</td>
<td>9.4</td>
<td>10.5</td>
<td>STRONG</td>
</tr>
<tr>
<td>Uranus</td>
<td>*76 K</td>
<td>10,000 kPa?</td>
<td>4.0</td>
<td>17</td>
<td>#Strong</td>
</tr>
<tr>
<td>Neptune</td>
<td>*72 K</td>
<td>MASSIVE</td>
<td>3.9</td>
<td>16</td>
<td>Strong</td>
</tr>
</tbody>
</table>

*Temperature at 100 kPa level  #Uranus has a weird tilt  ^dust storms affected
Earth’s Climate has always been changing.
Climate change over last 800,000 years

- CO₂
- Antarctic Temperature
- Ice volume proxy
- Sea level

IPCC (2013) Chap. 5 Fig 5.3

- Africa Exodus
- Europe
- Agriculture

Modern humans

400 ppm

8° C

100 m

Age (ka)
1) Is climate changing now?
Evidence for current climate change

“Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.” IPCC (2013)

Top: Differences in global average surface temperature compared to the 1961-1990 average
Middle: Changes in the July-September average summer Arctic sea ice extent
Bottom: Changes in global average sea level compared with 1900-1905 average

Source: IPCC WGI (2013) SPM
Indirect (or "proxy") observations must be used to piece together past climate. These help us to understand how climate has changed in the past and put current direct observations in context.

**GLOBAL, proxies, Marcott et al. (2013) Science**

**GLOBAL, Instrumental**

Northern hemisphere proxies
2) Why is Earth warming?
Changes in greenhouse gases from ice core and modern data

Carbon dioxide, methane and nitrous oxide

IPCC (2007) Summary for Policy Makers Fig. SPM.1
Satellite observations detect enhanced greenhouse effect: 1997-1970

These results showed for the first time experimental confirmation of the significant increase in the greenhouse effect from trace gases such as carbon dioxide and methane
"Radiative forcing" of climate

- Increases in greenhouse gases heat the planet by reducing how easily Earth can cool to space through infra-red emission
- More small pollutant “aerosol” particles cool the planet by reflecting sunlight
- If more energy is arriving than leaving, Earth should heat up...

Currently energy is accumulating at rate equivalent to 300 billion electric heaters (1 kilo Watt) spread over the globe
3) Can we explain recent warming?
Comprehensive climate simulations...
Natural factors cannot explain recent warming

See IPCC FAQ 10.1 and SPM Fig. 6
Recent warming can be simulated when man-made factors are included.

See IPCC FAQ 10.1 and SPM Fig. 6.
4) What are the predictions?
Future projections to 2100 from climate models

“Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.” [IPCC 2013 SPM]
European 2003 summer temperatures could be normal by 2040s, cool by 2060s
Long term forecast?

Future World + 250 Ma

PACIFIC OCEAN

Life Cycle of the Sun

Birth 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Sizes not drawn to scale

Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge
Extra slides
- Atmospheric moisture increases with warming in computer simulations and as detected by conventional and satellite observations.

- The enhanced greenhouse effect amplifies climate change (+ve “feedback”)

- Additional moisture also fuels a greater intensity of rainfall
But how will climate change regionally?
What explains the mild climate in the UK and its variations from year to year?

Mild ocean currents and atmospheric winds
1. Air is **warmer** closer to the tropics (air expands) than at the poles (air contracts). This generates a **poleward flow of air** high up in the atmosphere.

2. The Earth spins: the surface moves quicker near the equator than at higher latitudes. So poleward-flowing air retains this speed and is deflected to the **east** (direction of spin).

3. This high altitude (5-7km) fast moving ribbon of air is called the **jet stream**. It steers weather systems over or away from the UK.
Remote influences on the jet stream

4. Changes in this temperature difference between equator and pole can alter the position and strength of the jet stream. This and other natural and human-caused effects influence our weather patterns and extremes.
P. L. Read (Univ Oxford) after Trenberth et al. (2009) BAMS
Mars Dust storm season

Total shortwave reflected to space
43 W m$^{-2}$

Incoming Solar radiation (shortwave)
147 W m$^{-2}$

Absorbed by atmosphere
81 W m$^{-2}$

Reflected by atmosphere to space
33 W m$^{-2}$

Reflected by surface to space
7.5 W m$^{-2}$

Outgoing Infrared radiation (longwave)
106 W m$^{-2}$

Absorbed by atmosphere
93 W m$^{-2}$

Emitted by atmosphere to space
78 W m$^{-2}$

Longwave flux emitted by surface
100 W m$^{-2}$

Absorbed by surface
74 W m$^{-2}$

Absorbed by surface
25 W m$^{-2}$

Absorbed by surface to space
4 W m$^{-2}$

P. L. Read (Univ Oxford) after Lewis et al. (1999) JGR
Croll-Milankovitch Cycles

- **Eccentricity**: 100,000 years, 413,000 years
- **Precession**: 19–24,000 years
- **Tilt**: 21.5°–24.5°, Currently 23.5°
See also [IPCC (2013) Summary for Policy Makers](#) (Figure SPM.4)
Clouds and why global warming predictions are uncertain?
Climate variations over the last 400,000 years as recorded in Antarctic ice

* - indicates interglacial period

Inferred “proxy”
Temperature

Modern humans  Africa Exodus  Europe  Agriculture

Man-made CO\textsubscript{2} has diluted natural CO\textsubscript{2}

Theoretical

Tree Ring Observations
Energy from the Sun; stable over last 50 years

IPCC (2007) WG1 2.7.1 (p.188-193)

Lean (2000)
Y. Wang (2005)

See also: http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant
Changes in volcanic activity

IPCC (2007) WG1 2.7.2 (p.193-195)

Volcanic Aerosol Total Visible Optical Depth

Sato et al. (1993)
Ammann et al. (2003)

Estimated cooling effect, Wm$^{-2}$

Time (years)

Optical Depth

Sulphur aerosols cool climate directly and indirectly.
What would happen if we enhance the greenhouse effect?

Surface Temperature = +15°C

Solar

240 Wm\(^{-2}\)

Thermal

240 Wm\(^{-2}\)

390 Wm\(^{-2}\)

Efficiency ~61.5%

Radiating Efficiency, or the inverse of the Greenhouse Effect, is strongly determined by water vapour absorption across the electromagnetic spectrum.

\[
(1 - \alpha)S_o / 4 = \sigma T_e^4
\]

\(T_e\) is Earth’s effective temperature as seen from space.
Introduce a radiative forcing (e.g. 2xCO$_2$)
note: could equally choose to change solar

Solar: 240 Wm$^{-2}$

Thermal: less cooling to space

Efficiency $\sim 60.5\%$

Surface Temperature = +15$^\circ$C

Radiative cooling to space through longwave emission drops by about 4 Wm$^{-2}$ resulting in a radiative imbalance
The climate system responds by warming

Solar > Thermal

240 Wm$^{-2}$

236 Wm$^{-2}$

390 Wm$^{-2}$

Surface Temperature = +15°C

Efficiency ~60.5%
Doubling CO\textsubscript{2} concentrations increased temperature by about 1\textdegree C in this simple example. But this ignores feedback processes that may amplify or retard the response to the forcings.
Experiments with climate models

- How much of recent warming is explained by natural effects?
- To answer such questions, experiments can be performed with climate simulations
  - including just natural factors (ocean circulation, volcanic eruptions, changes in the sun, ...)
  - including natural and anthropogenic factors (e.g. greenhouse gas emissions which cause heating + sulphate aerosol pollutant particles which cause cooling)