Greenhouse effect

S = Solar radiation incident on surface of the Earth = **Solar constant** = 1.37 kWm^{-2}

A = Fraction reflected by clouds and surface of the Earth = **Albedo** ≈30%

Energy transmitted in vacuum by radiation. Enegy per unit time per unit area (i.e. power per unit area) is given by the **Stefan-Boltzmann** law:

$$P_e = \epsilon \sigma T^4$$

where,

P_e = power per unit area (also called **flux**)

ε = **emissivity** (a constant of value 0-1 depending on the nature of the surface, $\varepsilon = 1$ for a black body)

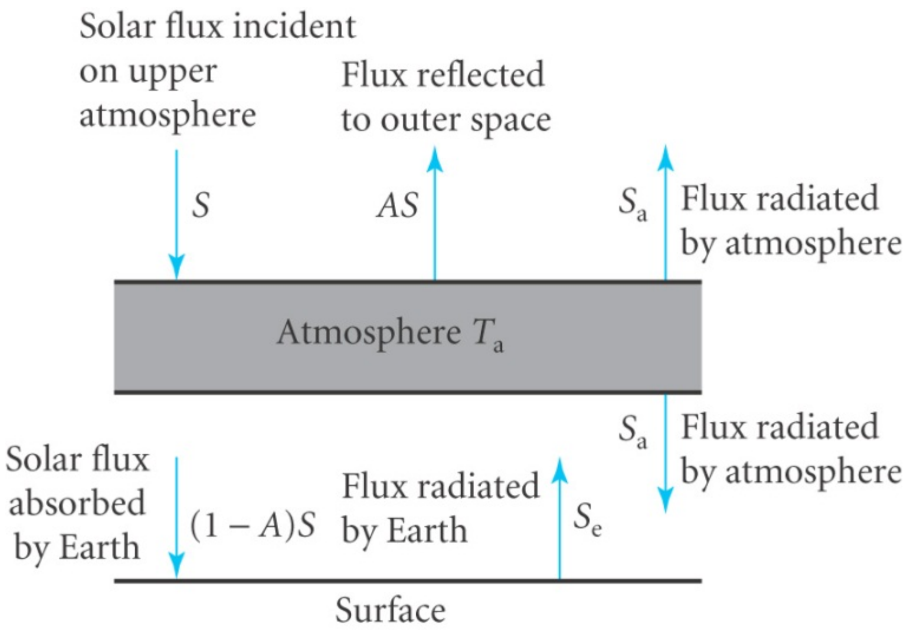
σ = Stefan-Boltzmann constant ≈ 5.67×10^{-8} Wm^{-2}K^{-4}

Exercise G1: Estimate the power radiated from a black body with a surface area of 1 cm^2 at a temperature of 1000 °C

Solar radiation in the **visible** part of the elecromagnetic spectrum

Room temperature radiation emitted by the Earth is in the **infrared** part of the electromagnetic spectrum

Geothermal heat flux « Solar constant



(Note that the only heat transfer to the atmosphere from the Earth is by radiation)

If atmosphere absorbs no radiation (solar radiation in the **visible** part on the spectrum (i.e. wavelength, $\lambda \approx 450$ nm – 1μm) and that $\varepsilon = 1$, at equilibrium:

Incident solar power = power emitted by surface of the Earth

$$(1-A)S\pi R^2 = 2 \times 2\pi R^2 \sigma T^4$$

Emission from whole of surface of Earth

Insert $A = 0.3$, $S = 1.37$ kWm^{-2}, find,

$$\underline{T = 255\ \text{K} = -18\ ^\circ\text{C}}$$

Consider if atmosphere absorbed all in infrared radiation emitted by the Earth but still transmitted all of the incident solar radiation.

Atmosphere heats up to T_a, such that:

Energy radiated into space by atmosphere = energy received by atmosphere

Assuming $\varepsilon = 1$ again,

$$4\pi R^2 \sigma T_a^4 = (1-A)S\pi R^2$$

(Assumed radius of Earth plus atmosphere ≈ radius of Earth)

So, $T_a = 255$ K = -18 °C

Radiation from atmosphere:

into outer space (up in diagram) = towards surface of the Earth (down in diagram)

Earth therefore receives more radiation and heats up to temperature T_E, so at steady state energy equilibrium:

$$(1-A)S\pi R^2 + 4\pi R^2 \sigma T_a^4 = 4\pi R^2 \sigma T_E^4$$

Insert the values of A, S, and σ used previously,

$$2T_a^4 \approx T_E^4$$

$$\underline{T_E = 303\ \text{K} = 30\ ^\circ\text{C}}$$

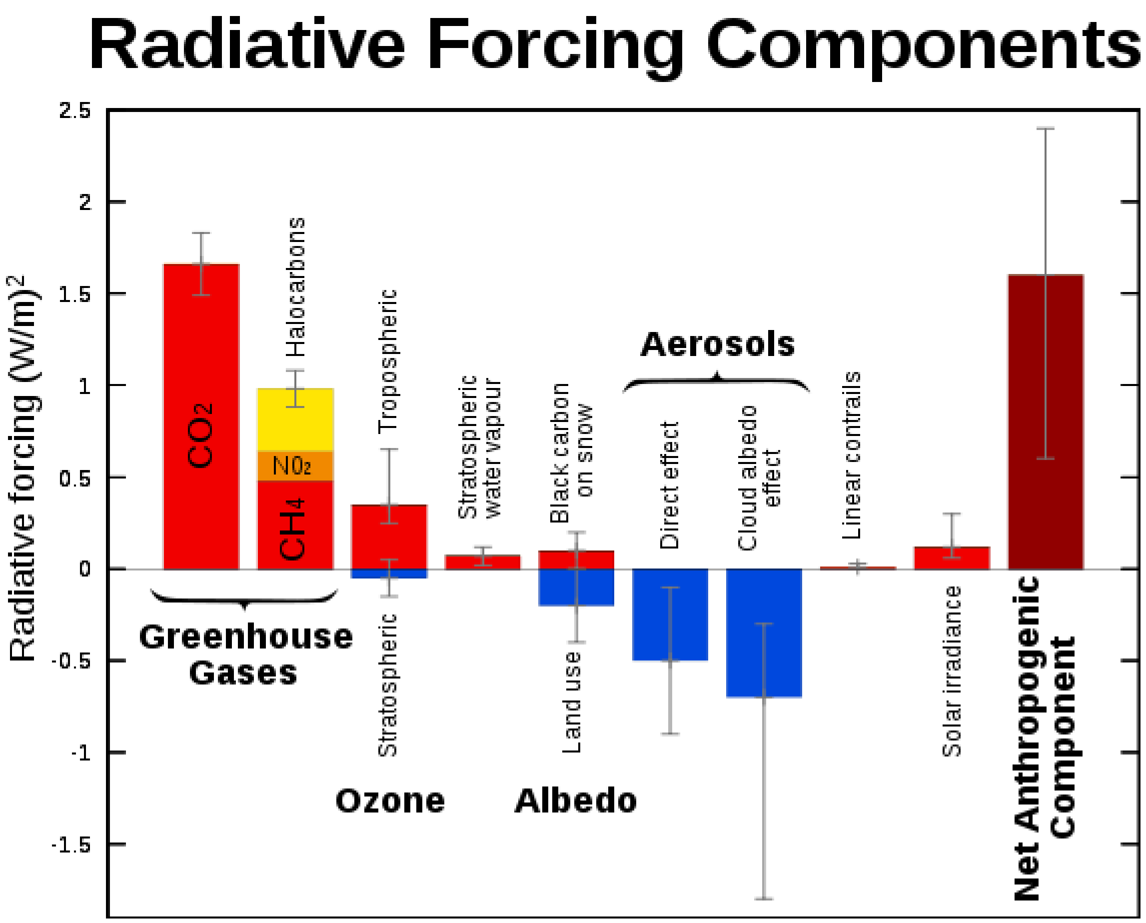
The rise in the surface temperature of the Earth due to absorption of infrared radiation is called the **greenhouse effect**.

Exercise G2: Consider the following simple model to describe solar radiation incident on Earth in which the atmosphere is included. A fraction f of the incident solar flux is absorbed by the atmosphere and a fraction A is reflected, the rest being absorbed by the Earth. Assume that the only heat transfer to the atmosphere from the Earth is by radiation and that $f = 0.25$ and $A=0.3$. Find the Temperature T_E of the surface of the Earth for radiative equilibrium.

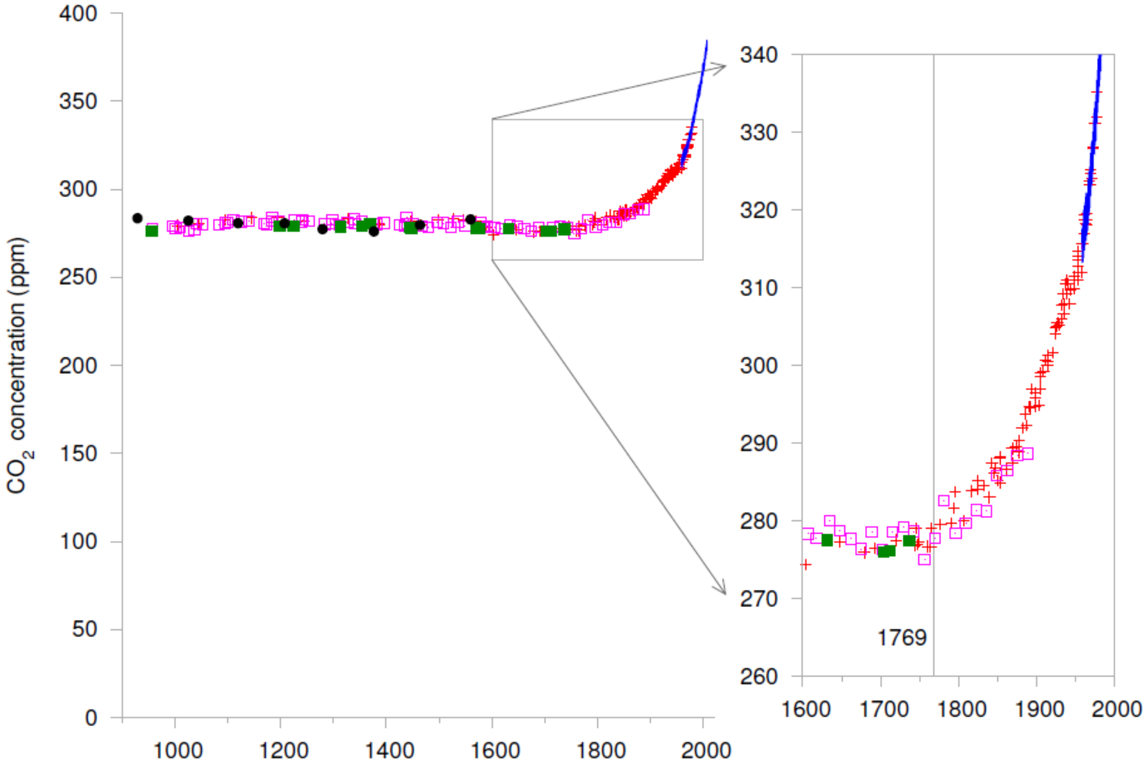
Radiative forcing

IPCC definition:

"Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in Watts per square meter (W/m^2)."



From: http://en.wikipedia.org/wiki/Radiative_forcing



Carbon dioxide concentrations in parts per million for the last 1100 years measured from air trapped in ice cores (from MacKay)

Radiative forcing the rate of energy change per unit area (units: Wm^{-2}) of the Earth as measured at the top of the atmosphere (troposphere) which results from a change in the heat balance at the troposphere due to a climate changing factor.

A +ve value means that the heat that escapes is less than that which comes from the Sun and the Earth will heat up.

A -ve value means that the heat that escapes is more than that which comes from the Sun and the Earth will cool.

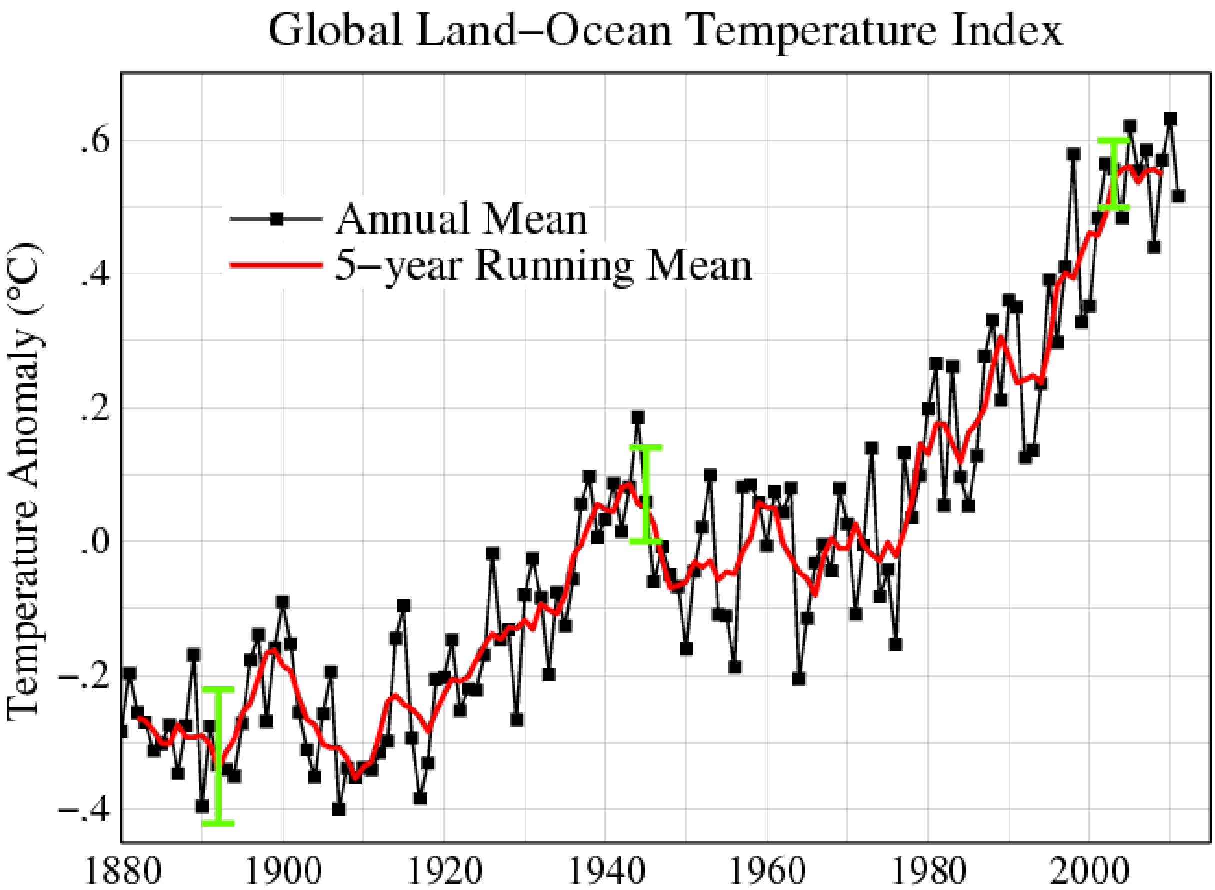
Another climate changing effect can counteract the radiative forcing, e.g. black body radiation (S is proportional to T^4 so the power output of the Earth increases with increasing temperature): this is referred to as **negative feedback**.

Positive feedback occurs when the climate changing factor has consequences which further warm up the Earth (e.g. as the temperature increases the polar ice -caps will melt and the fraction of the radiation from the Sun that is reflected will be lessened causing the Earth to heat up even more which causes more ice to melt, and so on.

Global climate models

We have used a simplified climate model (sometimes referred to as a 'box model') but there are many more sophisticated global climate models. There is a small research topic in Homework 2 directed at the physics these are based on, the predictions that can be made with them, and the factors which cause uncertainty in these predictions.

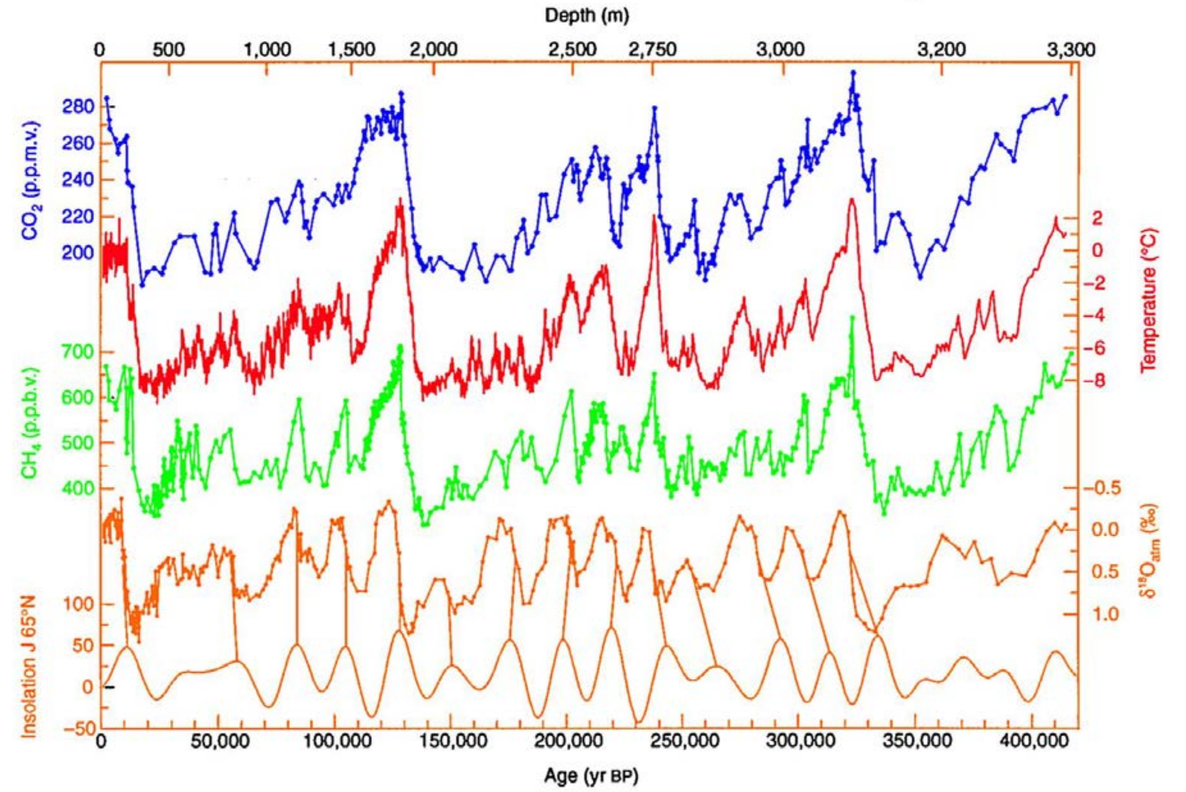
Average global temperature



Global mean land-ocean temperature index, 1880 to present relative to the 1951-1980 mean. The black line is the annual mean and the red line is the five-year running mean. The green bars show uncertainty estimates. The graph shows an overall long-term warming trend. In the 1890s, the global temperature anomaly was on average slightly below -0.3 °C, with an error range of roughly -0.2 and -0.4 °C. In the 1940s, the global temperature anomaly was on average slightly below +0.1 °C, with an error range of roughly 0.0 and +0.15 °C. In the 2000s, the global temperature anomaly was on average slightly below +0.6 °C, with an error range of roughly +0.6 and +0.5 °C. (From: http://data.giss.nasa.gov/gistemp/)

Milankovich cycles

Milankovitch theory describes the collective effects of changes in movement of the Earth upon its climate. Milanković mathematically theorized that variations in **eccentricity**, **axial tilt**, and **precession** of the orbit determined climatic patterns on Earth through orbital forcing.



420,000 years of ice core data from Vostok, Antarctica research station.

Current period is at left.

From top to bottom:

- Levels of carbon dioxide (CO_2).
- Relative temperature.
- Levels of methane (CH_4).
- ^{18}O isotope of oxygen.
- Solar variation at 65°N due to Milankovitch cycles (connected to ^{18}O). **Insolation** is a measure of solar radiation energy received on a given surface area and recorded during a given time.

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(From: http://www.usgcrp.gov/usgcrp/images/Vostok.jpg)