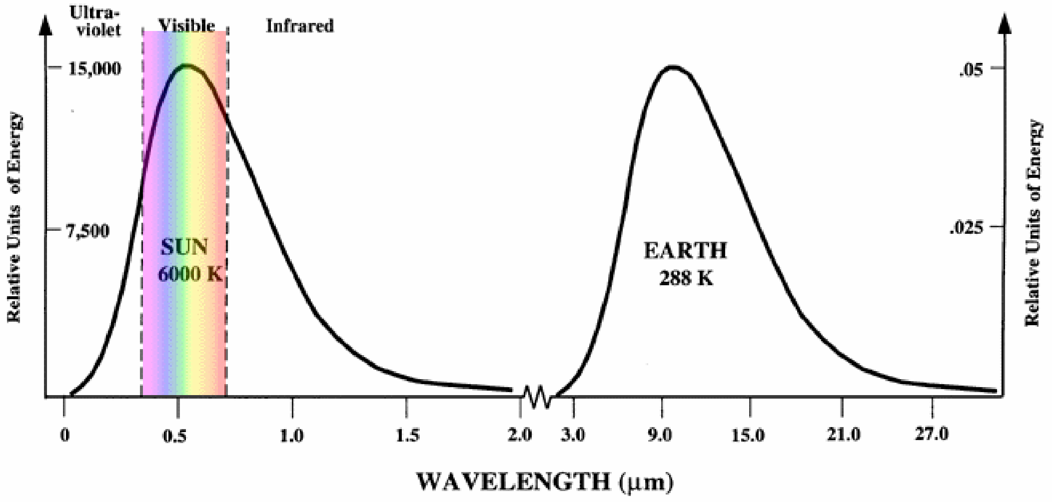
The Earth’s Radiation Budget

Solar energy is absorbed by the Earth, and drives the weather patterns and therefore the climate (average weather) that we observe. The only other source of energy at the Earth’s surface comes from the cooling of the interior of the planet, but this is about 2000 times smaller than the solar energy flux.

1) The Earth’s Radiation Budget



Comparison of the emission spectra of the sun and the earth. Note the huge disparity in the amount of energy emitted by the sun (left-hand scale) and the earth (right-hand scale).

Figure 1: Emission spectra from the Sun and the surface of the Earth. The Sun, at 6000K, emits much more radiation than the Earth, at about 283K, (note the difference in vertical scale) and in a different wavelength band.

The temperature of the Earth’s surface, atmosphere and oceans and the rate of change of those temperatures depends on the detailed balance of energy fluxes. Commonly referred to as the ‘radiation budget’, a simplified representation is shown in figure 2.

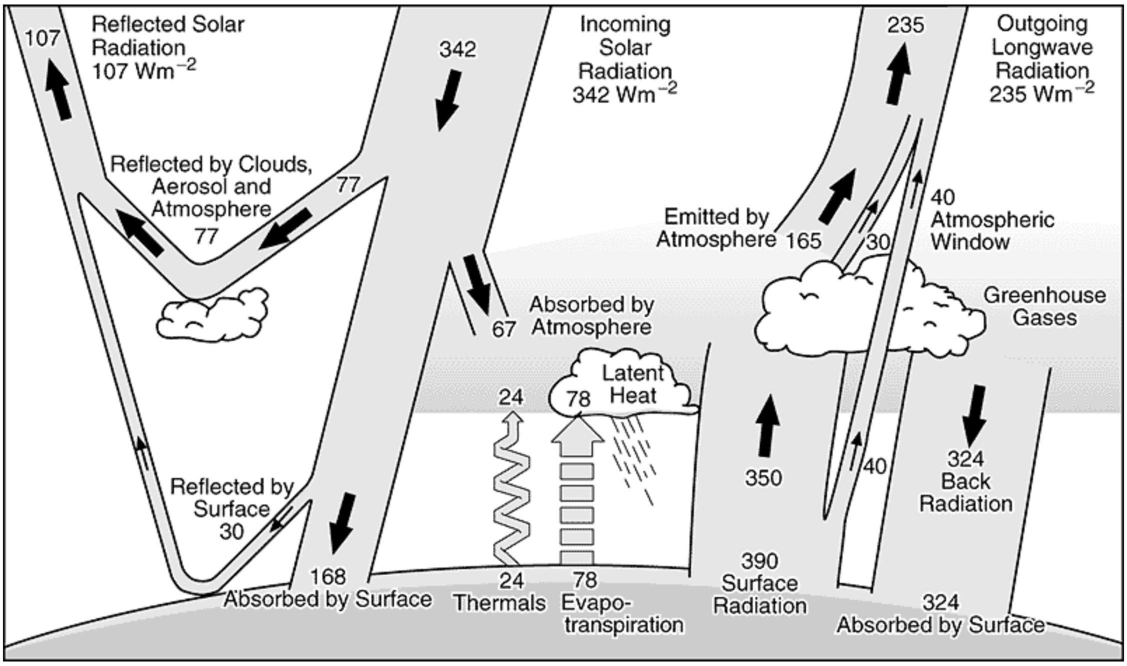


Figure 2: The Earth's radiation budget. Typical values of the albedo, or proportion of incoming radiation reflected, are 0.15-0.8 for clouds, depending on thickness and height, 0.8-0.9 for snow and ice, 0.35 for desert, 0.1-0.2 for forests and cities, 0.05-0.5 for water. Note that the incoming and outgoing radiation at the top of the atmosphere balance – this is no longer the case. If it were, there would not be a long term trend in the temperature of the Earth and atmosphere. The 'atmospheric window' refers to the wavelengths of outgoing radiation which are not absorbed by any atmospheric gas, and therefore escape to space unhindered. Source: IPCC

A simplified model of the greenhouse effect

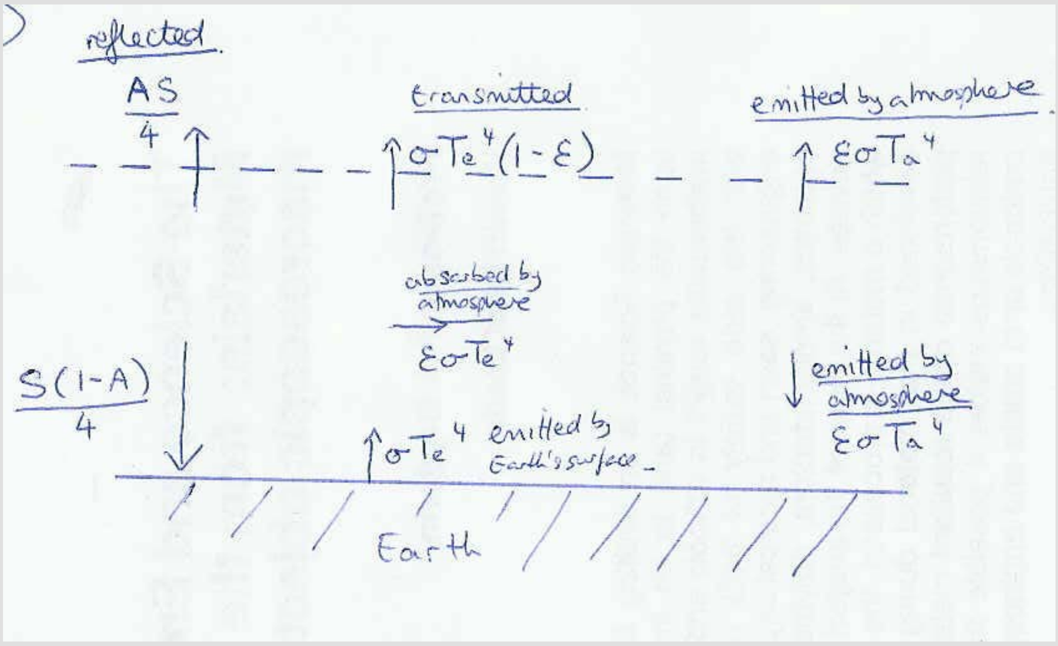


Figure 3: Simple model of Greenhouse effect. S is the Solar constant (the amount of energy

arriving per metre squared at the top of the Earth's atmosphere, here divided by 4 to take account of the fact that the Earth intercepts solar radiation as a disk of area πr_e^2, but radiates as a sphere of surface area $4\pi r_e^2$), A is the albedo, ε is the absorptivity/ emissivity of the atmosphere, σ is the Stefan-Boltzmann constant, T_e is the temperature of the Earth's surface and T_a is the temperature of the atmosphere. The dotted line marks the top of the atmosphere.

The effective temperature of the Earth, or the temperature of the Earth as calculated by an observer far out in space based on the radiation emitted, is about 250K. The average surface temperature, however, is about 33K warmer. This difference is maintained by the so-called greenhouse gases in the atmosphere; water vapour (the most important), carbon dioxide, methane, nitrous oxide etc., which act as a semi-opaque blanket to infrared radiation. The more opaque the blanket, the bigger the difference: 10K on Mars, nearly 500K on Venus.

Key points:
- with no greenhouse gases in the Earth's atmosphere, the temperature on the surface of the Earth would be, on average, about 33K cooler than it actually is.

2) Redistributing the Energy

The Earth's radiation budget is complicated by the fact that is a sphere, and a rotating one at that. Figure 3 shows how the curvature of the Earth's surface leads to a difference in the amount of incoming solar radiation per unit surface area at different latitudes.

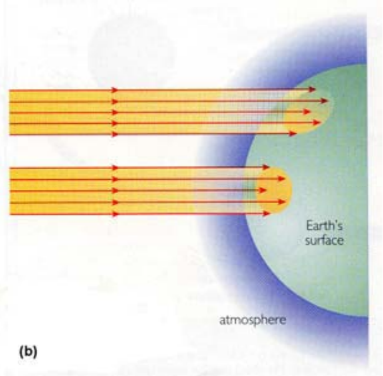


Figure 4: Schematic diagram of incident solar radiation.

Figure 5 shows the resulting latitudinal variation in solar energy absorbed (note that this will also be affected by latitudinal differences in how much incoming solar radiation is reflected by the atmosphere and surface). Much more solar radiation is absorbed in the tropics than at higher latitudes. The latitudinal variation in infrared radiation emitted by the Earth is also shown; it is greatest in the Tropics where it is warmest, and less from the cooler poles, but the pattern of outgoing and incoming radiation is not the same. The result is a net excess of heat in the Tropics and a deficit in polar regions. If some mechanism did not continually transfer heat polewards, the poles would cool, and the Tropics get warmer, until the two profiles were the same.

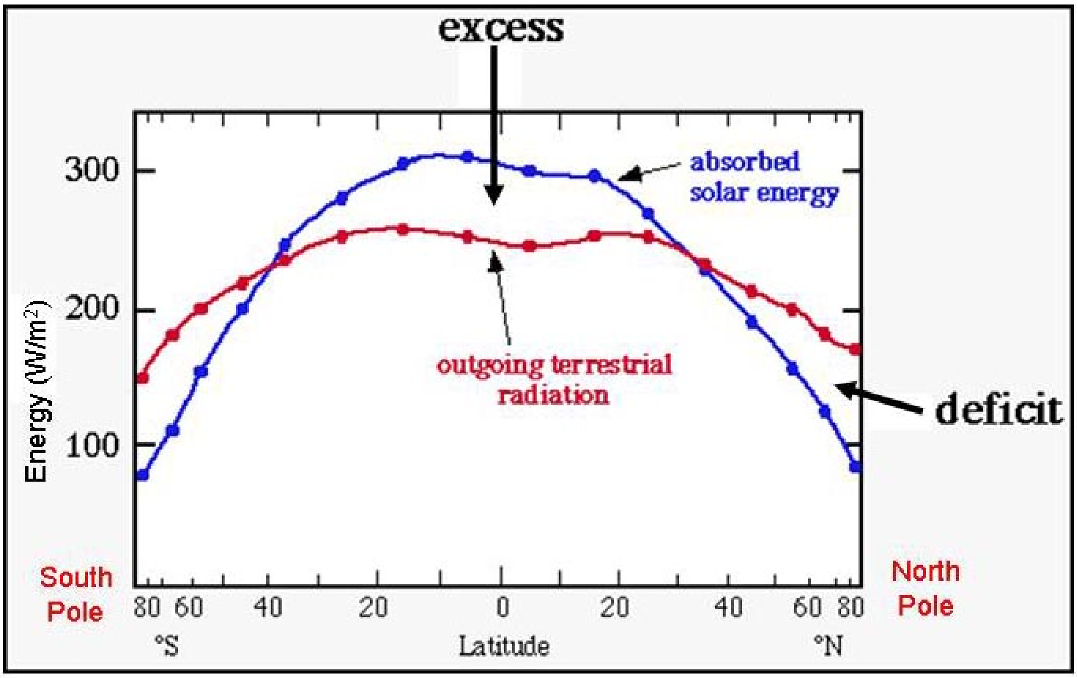


Figure 5: Latitudinal dependence in absorbed (blue) and emitted (red) radiation from the Earth's surface.

Three main mechanisms are responsible for the poleward transport of heat:

i) The large scale circulation of the atmosphere, driven by warm air expanding and rising and cold air flowing in to take its place.
ii) The large scale circulation of the oceans is driven both by differences in surface temperature, and by differences in salinity: ice forming in polar regions leaves relatively salty, and therefore more dense, cold water which will sink.
iii) Weather systems such as tropical cyclones and mid-latitude depressions, and particularly the latent heat associated with the formation of water droplets/ ice crystals, are responsible for the remaining poleward energy transport.

The Circulation of the Atmosphere is complicated by the rotation of the Planet – instead of one 'thermally direct' cell with air rising at the latitude perpendicular to the Sun where the ground is warmest and sinking at the Poles where the ground is coldest, the circulation breaks down into two thermally direct cells, the Hadley and Polar cells (see figure 6). Poleward and equatorward air motion is further complicated by the rotation of the Planet and the fact that air in contact with the ground at the Equator has greater easterly momentum than air further poleward. This 'Coriolis effect' results, for example, in air moving equatorward appearing to be deflected to the west. The average effect of the mid-latitude weather systems, in terms of the large scale circulation of the atmosphere, is the 'Ferrell cell' shown in figure 6.
Similarly, the full oceanic circulation is complicated by the presence of continents and the circulation of the Earth.

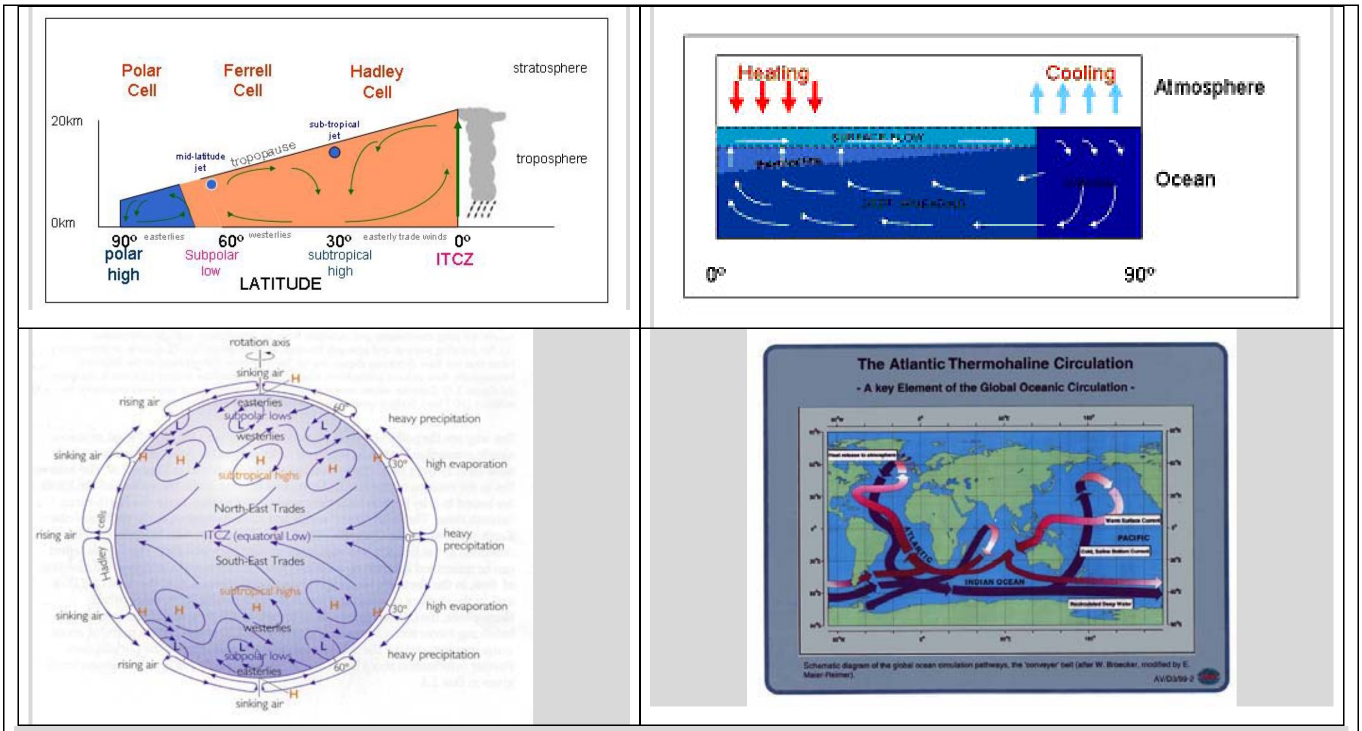


Figure 6: Simplified sections (top) and maps (bottom) of atmospheric (left) and oceanic (right) circulation.

Key Points:

- The Earth receives more solar radiation per unit area in the Tropics than at the Poles.
- The atmosphere and oceans transfer heat from the Tropics to the Poles. As a result, the Tropics are cooler, and the Poles warmer, than they would otherwise be.
- The Earth' rotation and asymmetric distribution of land complicate the convection-driven circulation patterns of the atmosphere and oceans.

3) The Earth's Changing Radiation Budget

The Milankovich-Croll Cycles

The combined gravitational effects of the Sun, Saturn, Jupiter and other planets cause the eccentricity of the Earth's orbit to vary from its most elliptical to almost circular on a 110000 year time scale. The Earth is currently closer to the Sun in Northern Hemisphere winter than in Southern Hemisphere winter. This results in changes in the solar constant; the current seasonal variation is 6.8%, so the 'constant' is far from being constant!

Two shorter cycles do not effect the solar constant, but do effect the distribution of radiation on the Earth's surface. The precession of the equinoxes is a gyroscopic motion due to the tidal forces exerted by the Sun and the moon on the solid Earth, associated with the fact that the Earth is not a perfect sphere but has an equatorial bulge. Currently, this means that Southern Hemisphere seasons are more extreme than those in the Northern Hemisphere. Changes in the tilt of the Earth's axis of rotation are also the result of the gravitational interaction of the planets; we are 'stabilised' by the moon. The greater the tilt, the greater the seasonality of the climate. Currently, the Earth is tilted at 23.44° from its orbital plane, half way between its maximum and minimum value, and the angle is currently decreasing.

Coupled with asymmetries in the distribution of continents etc., and feedback mechanisms (see below) these three mechanisms can lead to significant changes in the Earth's climate, including the transition to and from ice ages.

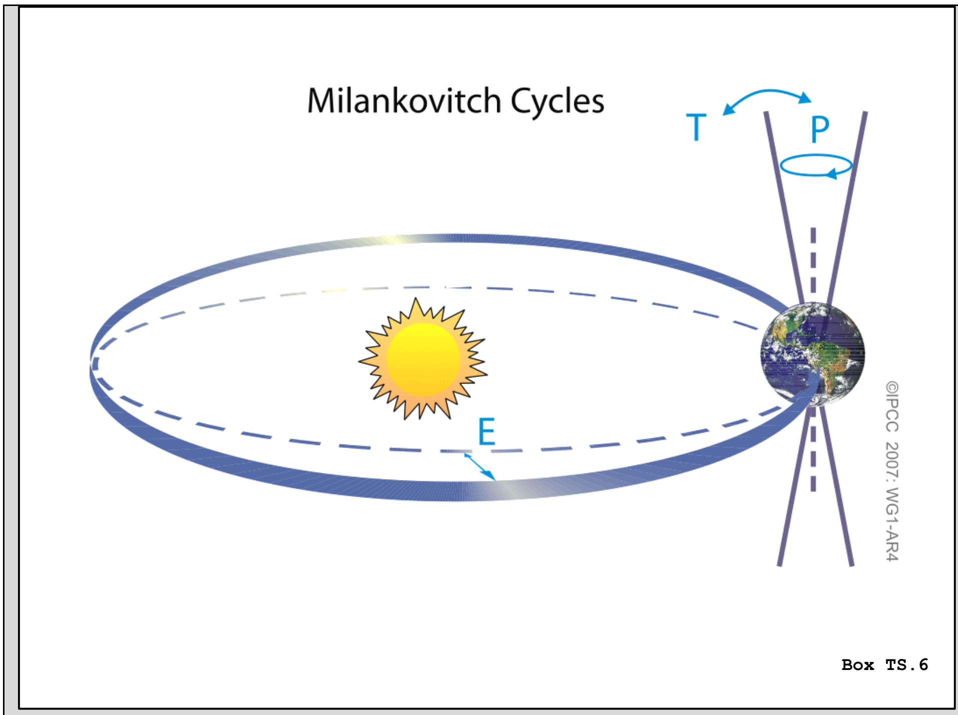


Figure 7: The three Milankovitch cycles. The tilt of the Earth's axis (T) varies on a 40,000 year cycle, the precession of the Equinoxes (P) on a 22,000 year cycle and the eccentricity of the Earth's orbit (E) on a 110,000 year cycle.

The enhanced greenhouse effect

Anthropogenic emissions of greenhouse gases since the Industrial revolution in the mid 18th century have led to a rapid rise in the concentration of greenhouse gases in the atmosphere. In 1859, John Tyndall's laboratory experiments showed that water vapour and carbon dioxide absorb infra-red radiation and that they could therefore affect the climate of the Earth. In 1896, Arrhenius estimated that a doubling of CO_2 would lead to a warming of 5-6 ºC. The observed concentration of atmospheric CO_2 has increased from 280ppm (pre-industrial) to well over 380ppm in 2008 and is rising by about 2ppm per year.

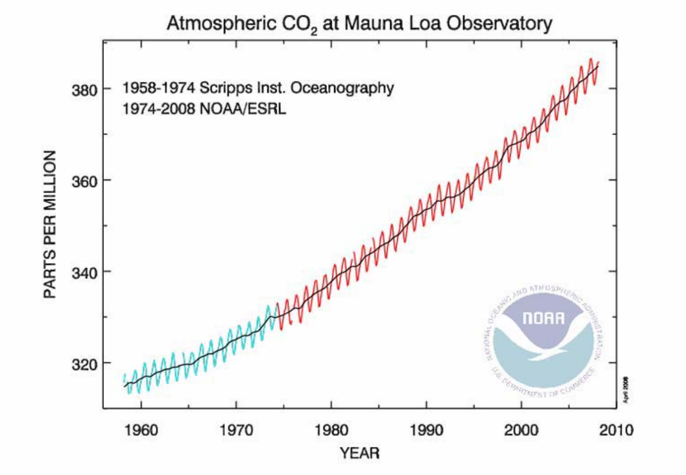


Figure 9: The concentration of Carbon Dioxide in the atmosphere as recorded at Mauna Loa observatory, Hawaii. Note the annual cycle: carbon dioxide tends to be released by plants in the autumn and taken up in the spring. As there is more land and therefore vegetation in the Northern Hemisphere than the Southern Hemisphere, we see more CO_2 in the atmosphere in Northern Hemisphere winter than summer.

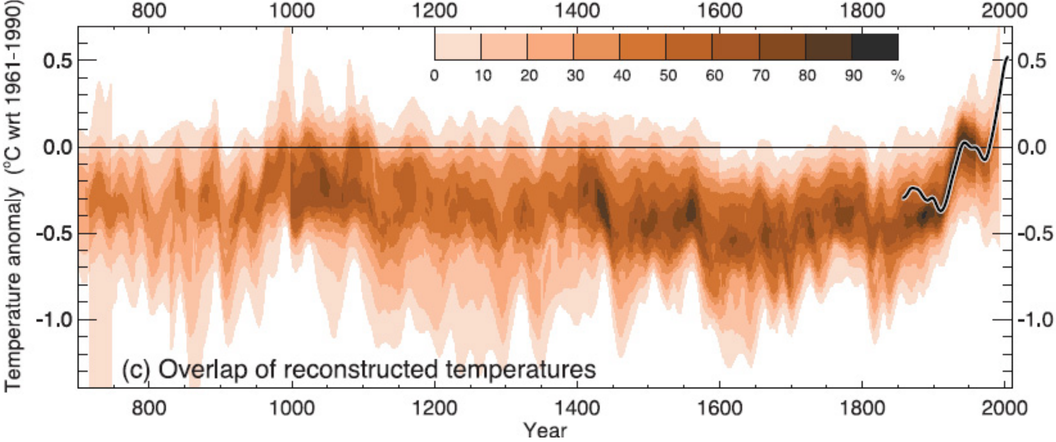


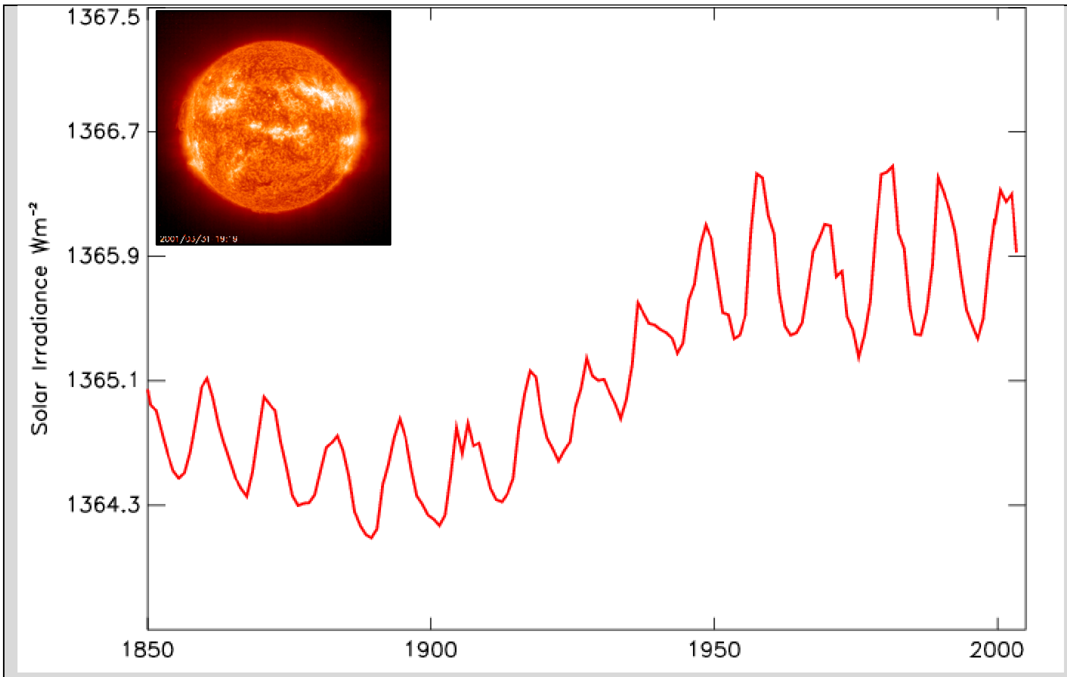
Figure 10: Reconstructions of past Northern Hemisphere temperature. Data sources include satellites, tree rings, ice cores etc. Source: IPCC 2007. Temperatures were barely 0.1ºC above the 1961-1990 mean in the ‘medievil warm period’ (around 1000AD) – significantly lower than current temperatures.

The direct effect of greenhouse gases on the Earth’s radiation budget (all that Arrhenius took into account) is however not the only mechanism whereby greenhouse gases can effect climate. There are numerous greenhouse gas - climate feedback mechanisms. Positive feedbacks include the melting of ice, leading to reduced albedo, the increase in water vapour, itself a greenhouse gas, in the atmosphere as a result of a more active water cycle, and the fact that the solubility of CO_2 in water decreases as the temperature increases, leading to the release of additional CO_2 from the worlds oceans. Negative feedbacks include increased uptake of carbon by oceanic biota, leading to a ‘biological pump’ moving carbon to the deep ocean on the death of the organisms, and an increase in photosynthesis by some plants (however an increase in plant and soil respiration may negate this).

Solar Activity

The Sun’s output of electromagnetic radiation is linked to the level of sunspot activity. Even though sunspots are darker than the rest of the solar photosphere, the Sun is actually slightly brighter (and the solar constant therefore slightly higher) when there are sunspots, because of the effect of other features that appear on the solar surface.

Scientific observations of sunspots began after the invention of the telescope, in 1610, and the approximately 11 year solar cycle, which can be seen clearly in figure 8, was identified in 1843. From 1645-1710 there were virtually no sun-spots; a period known as the Maunder minimum which has been linked to the ‘little ice age’ in the Northern Hemisphere.



Source: Lean, 2003

Figure 8: Solar irradiance over the past 150 years.

Changes in the solar constant through an 11 year cycle are typically less than 0.1%, with an estimated global temperature response of less than 0.03ºC. Nevertheless, some correlation has been noted with droughts, temperature, ozone etc. suggesting that there may be some feedback mechanisms. A cautionary note was added by Harry van Loon of the National Center for Atmospheric Research:
"The number of polar bears, the length of women's skirts, the stock market: Everything imaginable has been correlated with the solar cycle'.
There has been no net increase in solar brightness since the 1970s. Predictions for the next century suggest that there may be a slight reduction in sunspot number. A possible link between 'galactic cosmic rays' (high energy particles emitted by the Sun) and cloudiness is a subject of separate, currently well-publicised, debate.

Changes in the amount of incoming solar radiation reflected into space

Huge explosive volcanic eruptions in the Tropics, energetic enough to push sulphur gases up into the relatively stable stratosphere where they condense into aerosol (small particles), can have a cooling effect on climate by increasing the albedo of the atmosphere. The eruption of Pinatubo in 1992 resulted in a global cooling of up to half a degree for a couple of years. Other recent energetic eruptions include El Chichon (1982) and Agung (1963) which were preceded by half a century of little volcanic activity. The combined eruptions of La Soufrière (1812), Mayon (1814) and Tambora (1815) had catastrophic global effects, leading to a 'year with no summer' in 1816. A more dramatic change in albedo is associated with the 'snowball Earth' hypothesis. It has been suggested that during the Proterozoic (850-630 million years ago) the positive albedo feedback associated with ice accumulation led to ice covering the whole Earth. In this scenario, volcanoes and the huge amounts of greenhouse gases they can emit, would be necessary to break out of the ice-climate feedback.

The Earth's radiation budget is constantly changing, as day turns to night, season follows season, the composition of the atmosphere changes or the Earth's albedo changes. As a result, no component of the climate system ever reaches an equilibrium temperature, but is constantly adjusting. In general, the larger the change, or the greater the heat capacity of the component (oceans take longer to adjust than air), the longer equilibrium takes to achieve. Since the pre-industrial period, the Earth’s temperature has risen by 0.76 ºC ± 0.19 ºC, and is now rising more rapidly than at any other time in that period.