THE SCIENCE OF CLIMATE CHANGE[1]

The scientific chain of reasoning and evidence for human-induced global warming and ocean acidification are outlined. Appropriate responses are discussed.

Warm things emit heat radiation. Warmer things emit more heat radiation. The temperature of a planet, in a stable orbit, is that which balances the temperature-dependent outgoing heat radiation (long-wave or infra-red) with the (approximately fixed) incoming heat from the nearest star – in our case, the Sun. In the Earth's atmosphere, various gases (known as 'greenhouse gases') absorb some of that *outgoing* infra-red radiation and re-emit some part back to the Earth's surface, increasing the equilibrium temperature of the surface – *the greenhouse effect*. Some of these gases, such as carbon dioxide and methane, exist naturally in the atmosphere, but man's activity has increased their levels, creating a global heat imbalance known as the *enhanced greenhouse effect*. Basic physics therefore predicts that the Earth's temperature will increase over time until the net radiation is again in balance – *anthropogenic (human-induced) global warming (AGW)*. Every year, humanity adds (a currently increasing) quantity of greenhouse gases to the atmosphere through the burning of fossil fuels, land use change, industry and agriculture, raising further the concentrations of greenhouse gases, and therefore increasing further the heat imbalance (known as 'radiative forcing').

The total response of the earth system is enhanced by various 'positive feedbacks' (amplifications), including 'fast feedbacks' over days (associated for example with the additional water vapour held by warmer air) and 'slow feedbacks' over decades (associated with temperature-induced changes to the albedo (reflectivity) of the Earth and the carbon cycle). Simple physical systems often exhibit dominantly negative feedback in response to small perturbations (forcings) but positive feedbacks may become more dominant once a threshold ('tipping point') is passed. It is possible that the global climate system exhibits similar behaviour, with cyclical and chaotic behaviour too.

Human activity also exhibits various inertias (for example associated with sunk investment in energy infrastructure) analogous to the 'stopping distances' associated with halting a car on a motorway in response to stationary traffic ahead. A driver of a car must look ahead to see an upcoming hazard and respond in advance of meeting it. Analogously, an appropriate response to the threat of human-induced climate change needs to foresee the threat and respond in advance, avoiding the danger.

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) signed at the Rio Earth Summit' and ratified by 192 nations, including the United States and China (UNFCCC 2007), is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (U.N. 1992). After advice from scientists on the threats associated with global warming (including the melting of the Greenland ice sheet, and the possibility of temperature-induced methane or CO_2 release from carbon sinks) and the acidification of the oceans, governments have agreed to aim to limit global temperature rises to less than 2 Celsius above the pre-industrial level (UNFCCC 2009). For a *likely* chance of meeting this '2 degrees target', *concentrations* of greenhouse gases in the atmosphere must be stabilized at *close to or below current levels*. To achieve this, *emissions* of greenhouse gases should be reduced rapidly to below the rate at which they are absorbed by natural systems.

To preserve the climate in which human civilization has developed and prospered, it is necessary to move rapidly and globally to a *net-zero carbon economy*.

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Climate Physics

Introduction

In this section, the basic physical science[2] behind climate change is explained[3]:

1. The reasons why certain gases keep the earth warmer than it would otherwise be;
2. How elevated concentrations of these 'greenhouse gases' will warm the planet further.

There are three additional factors which complicate our attempt to understand the Earth system:

3. The temporary dimming effect of some of our other pollution;
4. Various positive and negative feedbacks, which tend to dampen and accentuate the effect of greenhouse gases;
5. The thermal inertia and consequent lagged response of the climate system.

Introducing the Earth

The Earth is a ball of rock with diameter 12,750 km and circumference 40,000km[4]. It lies in space, 150 million km from our nearest star, the sun[5].

The power or flow of energy, is measured in Watts (W). The flow of heat radiation is measured in Watts per square metre (Wm^{-2})

The sun emits approximately 3.9×10^{26} Watts of electromagnetic radiation (heat, light, etc.).[6] This amounts to an incident radiation intercepted by the Earth's cross-section area πr^2 of about[7]
$S = 1370\ Wm^{-2}$

The Earth's albedo, A, is the proportion of this energy which is directly reflected back (approximately 30%).
$A = 0.3$

The earth's total surface area $4\pi r^2$ is four times the Earth's cross section, and so the average heat radiation incident on the Earth's surface is:
$H_{total} = \frac{1}{4}S = 344\ Wm^{-2}$

Once we account for the Earth's albedo, the total absorption is:
$H_{input} = \frac{1}{4}S\ (1-A) = 240\ Wm^{-2}$

The light which is not reflected is absorbed by the Earth's surface and re-emitted as longwave radiation, such that the planet is in overall thermal equilibrium with the rest of the universe.

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[2] A more complete discussion might start from a description of the whole climate system (including transport of heat via atmospheric and oceanic circulation etc, as well as radiation), and the variations in global temperature etc. which are produced by solar/oceanic/volcanic etc. variation. We would then aim to discern the effect of CO_2 on this complicated system.

[3] We follow Archer (2007) also with some reference to Taylor (2005). For a more in depth treatment (also dealing with the climate of other planets) please see Pierrehumbert (2010).

[4] The technical name is an 'oblate spheroid', or 'a slightly flattened sphere' meaning that the earth is slightly more wide than it is tall. The diameter average is 12,742 km across. The spin of the planet causes the equator to bulge out further than the poles. Measured from pole to pole, the diameter of Earth is 12,713 km across. And measured across the equator, the Earth's diameter is 12,756 km across. In other words, points on the equator are about 21 km further from the center of the Earth than the poles. The Earth's Circumference = π* Earth's Diameter ≈ 3.14*12,750km ≈ 40,000km. See Universe Today (2009a).

[5] 1AU or 149,597,870km on average (UniverseToday 2009b).

[6] The sun has an effective temperature of about T_{SUN}=5780K giving the power output 390 million ExaWatts (Taylor 2005). The cross sectional area of the earth of radius r is $\pi r^2 = 3.14*6375^2 = 127.6$ million km^2. The area of the sphere at the earth's distance from the sun (R) is $4\pi R^2 = 4*3.14*(1.5x10^8)^2 = 2.81x10^{17} km^2$.

[7] Following Gill (1982, p.3). Compare Archer (2007, p.21)

What Would The Temperature of the Earth Be Without the Greenhouse Effect?

A body that emits all frequencies of light is known as a 'black body'. The Earth can be treated as a black body with albedo of 0.3 (Archer 2007). The heat out is given by $H_{out}=\sigma T_E^4$

The total energy radiated from the Earth is given by[8] $E_{out}=4\pi R_{Earth}^2 \sigma T_E^4$ (1)

For equilibrium this must be equal to the energy coming in from the Sun:
$E_{input}=(1-A)S\pi R_{Earth}{}^2$ (2)

From equation (1), the effective temperature of the Earth should be $T_E=\left(\frac{E_{input}}{4\pi R_{Earth}^2 \sigma}\right)^{1/4}$

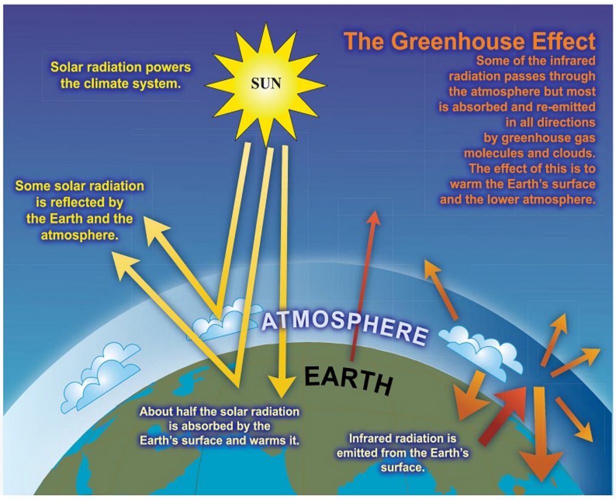
Substituting equation (2) for $E_{E,}$ gives $T_E=\left(\frac{(1-A)S}{4\sigma}\right)^{1/4}$

Substitution of numerical data for: Albedo A: 0.3; Solar constant S: 1370W/m2 and σ, gives a **predicted temperature of 255K or -17°C** for an earth without an atmosphere.

The **actual temperature of the earth is 287K or 14°C** [9]. What explains the difference?

The 'Greenhouse Effect'

Some of this re-emitted longwave (infrared) radiation is absorbed by certain molecules in the Earth's atmosphere leading to the 'greenhouse effect'.[10]



FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

It is known that greenhouse gases such as carbon dioxide and methane absorb heat re-emitted by the Earth, trapping the heat on the surface, just like the panes of glass in a greenhouse trap the heat inside.

The absorption bands in the infrared of gases such as Carbon Dioxide (CO_2) and Water (H_2O) are associated with 'bending' of the molecular structure (see arrows). Such bending resonances only

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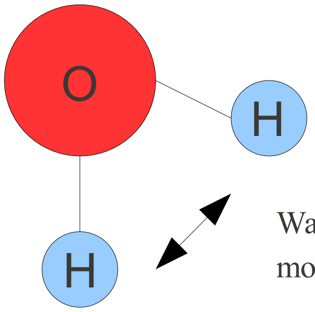
[8] See Wikipedia (2009)

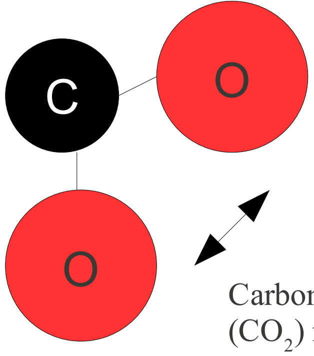
[9] It is clearly a simplification to summarize the Earth's temperature by a simple average, but as Archer (2007, p.55) points out, since the range of temperatures seen on earth is small compared to the absolute temperature, the black body energy flux curve as a function of temperature can be approximated by a straight line.

[10] Figure taken from IPCC (2007a)

exist for molecules with three or more atoms. The majority of the atmosphere is composed of diatomic molecules such as Nitrogen and Oxygen, which do not therefore act as greenhouse gases.

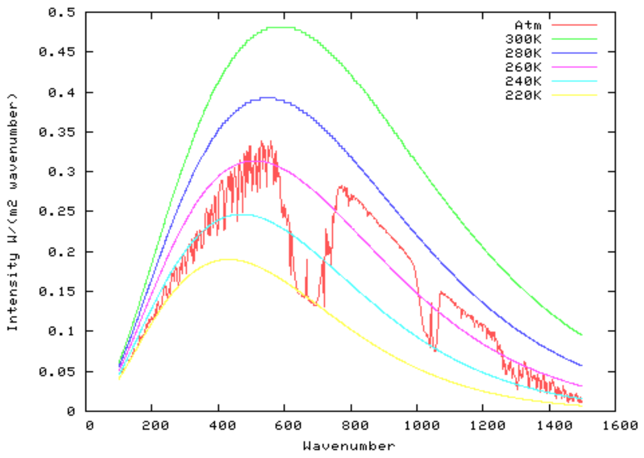


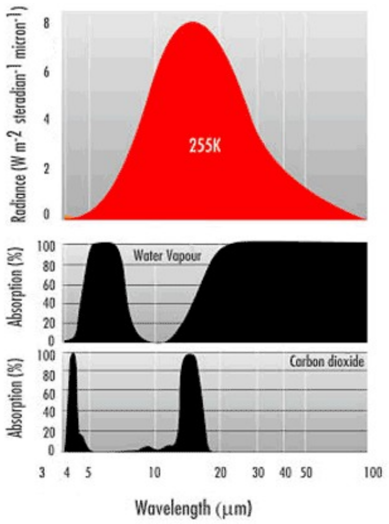
Water (H_2O) molecule



Carbon Dioxide (CO_2) molecule

The specific resonances that are in the centre of the infrared spectrum (below) are 'bending moments' associated only with molecules that have more than two atoms (above). The absorption spectrum of the Earth's atmosphere shows the absorption of carbon dioxide at 650 cm^{-1} (15 mm)





and water[11].

What would the temperature be with a 100% effective greenhouse?

We can make a simple 'slab' model of the Earth, such that the expected temperature would be[12]:

$$\sqrt[4]{2}*255=303\text{K}=31\,Celsius$$

It is difficult to determine from first principles what the temperature of the modern earth with greenhouse gas concentrations undisturbed by human intervention. However, we already know the answer to that question: the temperature of the earth before industrialization was approximately 13.7 Celsius.

How has human activity altered the Greenhouse Effect?

Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is changed when factors that affect climate are altered. It measures the initial effect of the greenhouse gases on the Earth's heat balance, excluding the feedbacks and increased heat outflows associated with increased temperatures[13].

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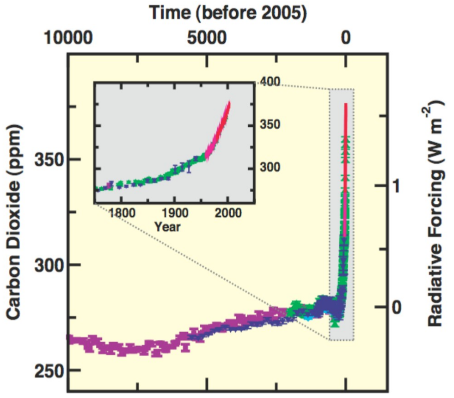
[11] *Left*: model results from Archer (2007). Available at: http://geodoc.uchicago.edu/Projects/modtran.doc.html

[12] See Archer (2007). On the Kelvin temperature scale 0°C=273.15K. Further simple models of the earth's warming are available from Real Climate blog: see Schmidt (2007)

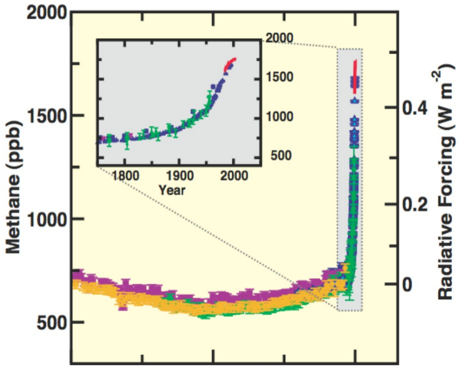
[13] Radiative forcing is defined as follows (IPCC 2007a): “The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm-2) at the tropopause AFTER allowing for

The first calculations of this question were made by Svante Arrhenius (1896). Arrhenius measured the absorption of the atmosphere by observing the moon's reflection of Earth's radiation. Through his keen observations he was able to deduce that the absolute warming (or cooling) that would take place from doubling (halving) the concentration is equal – in other words equilibrium temperature is proportional to the logarithm of the concentration of carbon dioxide.[14]

"The radiative forcing for pure CO_2 *is approximated by* $RF = \alpha \ln(C / C_0)$ *where C is the present concentration, α is a constant, 5.35, and* C_0 *the pre-industrial concentration, 278 ppm..."*[15]



Radiative Forcing Due to Carbon Dioxide (CO_2)



Radiative Forcing Due to Methane (CH_4)

Since they are present in much smaller quantities than CO_2, the radiative forcing associated with other well mixed greenhouse gases is approximately proportional to the concentration of those gases (rather than to the logarithm of the concentration).

The radiative forcing of all greenhouse gases can be translated into an 'Equivalent Carbon Dioxide' value CO_2e: *"...The value of* CO_2e *for an arbitrary gas mixture with a known radiative forcing is given by* $C_0\exp(RF / \alpha)$ *in ppmv."* (IPCC 2001).

Conclusions for Temperature Change

The outgoing heat flow can also be determined from the Stefan Boltzmann law. $H_{out} = \sigma T_E^4$
Differentiating this equation gives:

$$\frac{dH_{out}}{dT} = 4T_E^3 = 4\frac{H_{out}}{T}$$

At thermal equilibrium $H_{out} = H_{input} = 240Wm^{-2}$

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stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. "

[14] A sketched physical motivation follows:

We approximate the absorption at different wave numbers to follow an exponential distribution around a core wave number and assume that the absorption is proportional to the concentration of carbon dioxide until saturated, i.e.:

$$y = \begin{cases} f(n) & \text{if } f(n)<1 \text{ and} \\ 1 & \text{if } f(n)\geq 1 \end{cases}$$

where $f(n) = a.C.e^{-|n-n0|}$

and n is the wave number; n_0 is the centre of the peak; C is the concentration; a is a constant

The radiative forcing at different frequencies is approximately equal to the integral over all wave numbers. Letting $f^{-1}(x) = -Ln(x/(aC)) + n0$ and neglecting the area with $f(n)<1$, the total area of absorption large A is approximately

$RF = 2f^{-1}(1) = 2Ln(aC) = bLn(C) + d$

$\mathbf{RF = bLn(C) + d}$

where b and d are constants; RF is radiative forcing and C is the concentration of carbon dioxide.

[15] Alternatively $RF = 3.7*\log_2(C / C_0) = 3.7*\ln(C/C_0)/Ln(2)$

$$\frac{dH_{out}}{dT}=4\frac{H_{out}}{T}=\frac{4*240}{287}=3.36\,W/(m^2\,K)$$

For small changes in the temperature, we can assume that

$$H_{out}(T_0+\Delta T)\approx H_{out}(T_0)+\Delta T\frac{dH_{out}}{dT}$$

where $H_{input}(perturbed)\approx H_{input}(preindustrial)+\Delta RF$

and $H_{out}(T_0)=H_{input}(preindustrial)$

Assuming no feedbacks, this implies:

$$\frac{dRF}{dT}=\frac{dH_{out}}{dT}=3.36\,W\,K^{-1}\,m^{-2}$$

or $\frac{dT}{dRF}=\frac{1}{\frac{dH_{out}}{dT}}=0.3\,K\,W^{-1}\,m^2$

This can be compared to the instantaneous sensitivity to solar irradiance (see below).

Implications for Climate Sensitivity

$$T_{equilibrium}=a\log(C)$$

*(Where C is the concentration of Carbon Dioxide in ppm.)*or

$$T_{equilibrium}-T_{preindustrial}=Z\,.\,\log_2\left(\frac{C}{C_{preindustrial}}\right)$$

(Where the logarithm is taken to base 2, $C_{preindustrial}$ is the concentration of Carbon Dioxide before industrialization = 278 ppm where Z is the climate sensitivity measured in K increase for a doubling of CO_2)

or

$$T_{equilibrium}-T_{preindustrial}=\frac{Z}{\ln(2)}*\ln\left(\frac{C}{C_{preindustrial}}\right)$$

Climate sensitivity Z is defined as the equilibrium warming for a doubling of CO2.

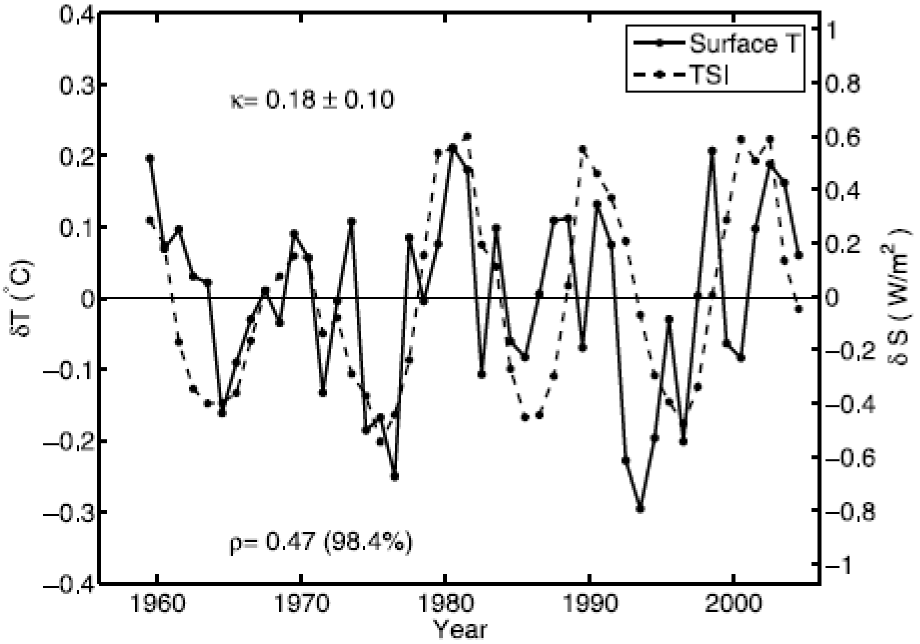
$$\Delta T=\frac{dT}{dRF}\Delta RF=5.35\ln\left(\frac{C}{278}\right)=\frac{dT}{dRF}*4\ln_2\left(\frac{C}{278}\right)=Z\ln_2\left(\frac{C}{278}\right)$$

$$Z=4*\left(\frac{dT}{dRF}\right)=4*0.3=1.2$$

For a dry greenhouse with only CO_2, the temperature should increase by approximately 1.2 Celsius for a doubling of pre-industrial CO_2 concentrations.

The Role of the Sun

Total solar irradiance (TSI), varies on a roughly 11-year cycle by about 0.07% (Camp & Tung 2007) or about 0.2W/m^2 on total heat inflow of $H_{input} = 264\ Wm^{-2}$.



Camp and Tung (2007) found that global temperature was correlated with Total Solar Irradiance (TSI) with a rise of 0.18 ± 0.08K per Wm^2 of radiative forcing or 4*0.18/(1-0.3)=1.03K per Wm-2 of absorbed radiation.

Instantaneous Climate Sensitivity

This value of 1.03 ± 0.46 K per Wm^2 can also be compared with the CO_2 only full sensitivity of 0.3K per Wm^2 and the standard model-estimated sensitivity (IPCC 2007a)of around 0.75 K per Wm^{-2}.

Unfortunately, however, life is not that simple. There are further complications which limit the accuracy of our models and also limit the information that we can deduce from observations of the world.

Complication One: Global Dimming

In addition to the effects of carbon dioxide, methane (CH_4) nitrous oxide (N_2O) and halocarbons (the main greenhouse gases)[16], there are other influences on the Earth's climate. These include ozone, stratospheric water vapour, surface albedo contrails; the net effect is small and uncertain.

Much of the warming effect is being offset by the other pollution that we emit, including aerosols such as sulphur dioxide. Aerosols are thought to dim the planet by approximately 1.2W/m^2, reducing the effective greenhouse gas concentration by about 90ppm CO_2^e.

They cause dimming both directly and because they act as condensation nuclei for clouds. The

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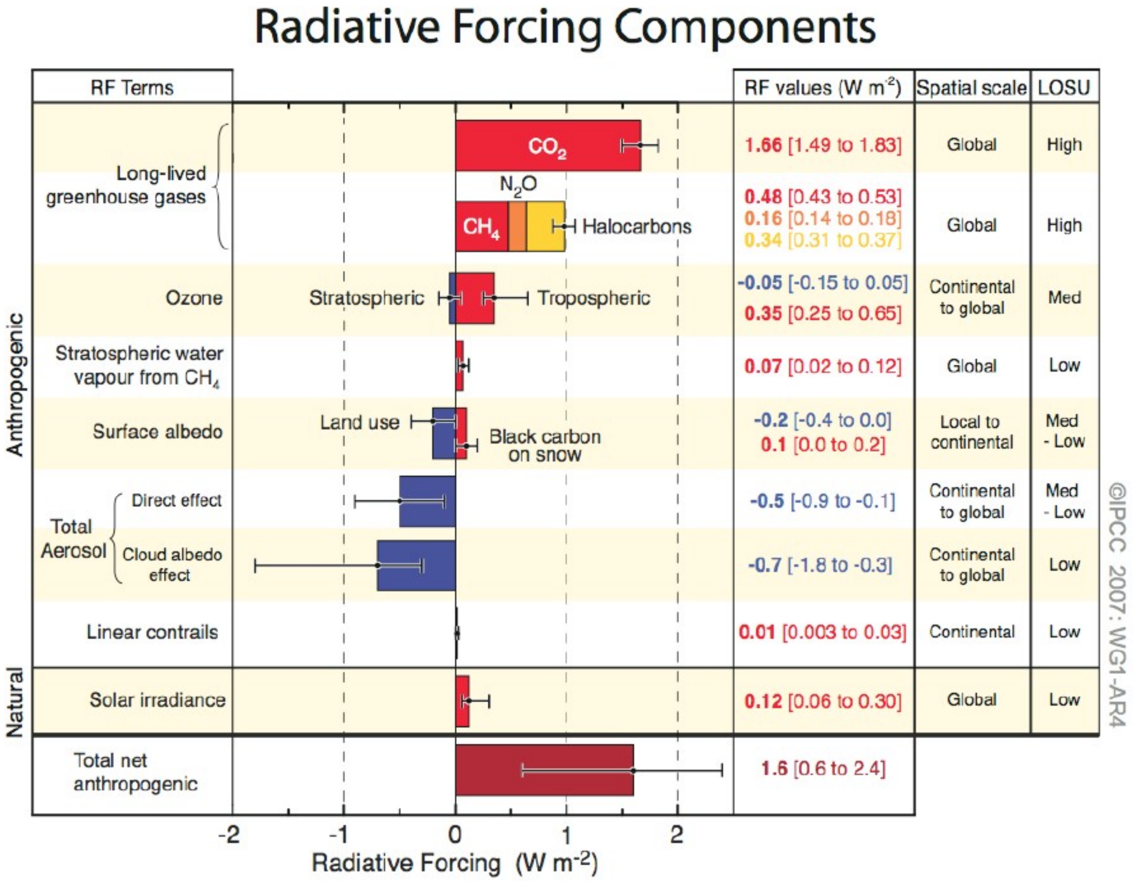
[16] The six gases (CO_2, CH_4, N_20, SF_6, HFCs) mentioned in the Kyoto protocol; plus CFCs (which are regulated under the Montreal Protocol)

second effect is highly uncertain, with the uncertainty as great as the purported effect. Nevertheless, evidence that it is a real effect can be found from the clouds that can be seen in the wake of ships sailing on the open ocean (Archer 2007).

Overall Contributions to Radiative Forcing

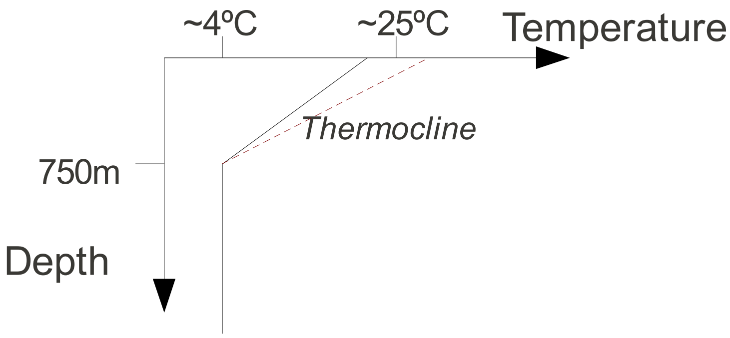
The contribution to radiative forcing of various gases is described here (IPCC 2007a).



Complication Two: Lag in the Oceans

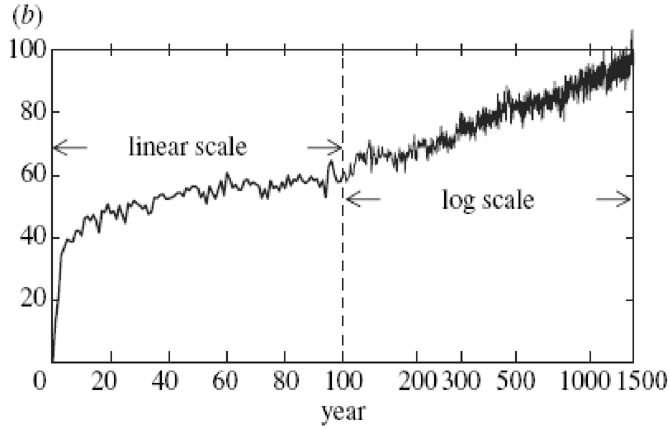
There is expected to be a lag in response to carbon dioxide to do with the thermal inertia of the oceans. A simple estimate for the lag in the oceans can be calculated by looking at the temperature profile of the oceans.

Forcing from above is expected to increase the upper ocean temperature. Global warming is unlikely to change the qualitative structure of the oceans' temperature gradient: therefore, by symmetry, climate change is likely either to increase the gradient of the ocean thermocline as shown below (Houghton 2004).



Using this simple model, a heat capacity can be calculated, of approximately 30 years[17]. This can be compared to model estimations (Cess & Goldenberg 1981) of about 20 years.

These approximate estimates can be compared to the climate response found from a General Circulation Model (Hansen et al. 2007). 40% of climate response happens within 3 years; 60% within 100 years and it takes 1500 years for 95% of the response to have taken place.[18]



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[17] Author's calculation based on a wedge of water from zero to 750m deep.

[18] Assuming Camp & Tung's (2007) results, we might expect that our best guess for climate sensitivity is around (0.18/0.4)=0.45 K per Wm^2, or around 1.8K per doubling. This excludes, however, the longer-term, mostly positive 'slow' feedbacks.

Feedbacks and Systemic Effects

A complex physical system such as the earth's climate contains both negative and positive feedbacks.
The outputs (e.g. Temperature) of a system responds to inputs (e.g. Greenhouse Gas Concentrations). If the outputs then affect the inputs to the system in some way, then we have a feedback. There are two basic types of feedback, negative and positive[19]

A negative feedback (or natural stabilizer) is a feedback which acts to counteract the original change. Negative feedbacks are good if we want a stable life!

A positive feedback is one that tends to accentuate the original change. Positive feedbacks themselves are of two general types:

Complex systems tend to have both positive and negative feedbacks. For small perturbations, negative feedback effects may dominate; otherwise the system would not persist at this point. However, such systems may have a 'tipping point' past which the positive feedback effects may overwhelm the negative feedback loops.

Complication Three: Fast Feedbacks such as Water Vapour and Clouds

Carbon dioxide is not the only three-atom molecule present in reasonably large abundance in the earth's atmosphere. Water vapour is also extremely abundant, and furthermore, absolute humidity rises with temperature.

Furthermore, we know the rough magnitude of the relationships involved. As Arrhenius pointed out, the relative humidity will stay roughly constant as the temperature increases. Increases in the concentration of CO_2 will therefore also increase the level of absolute humidity (For every degree C of warming the absolute amount of water vapour should go up by about 6%) (Wexler 2007).

Influence of Climate Feedbacks

The relative importance of various climate feedbacks is available in the IPCC report, figure 8.14. This diagram shows that water vapour is the most important positive feedback in determining the basic climate sensitivity; as the world warms, the atmosphere's absolute humidity will rise, trapping more heat (since water vapour is a greenhouse gas).

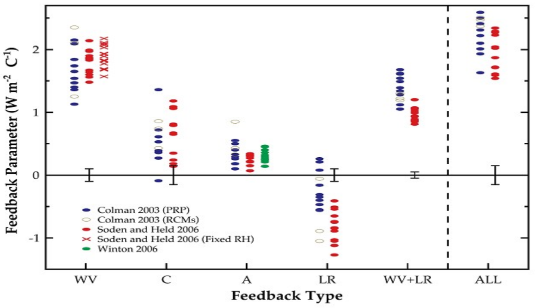

Figure 8.14. *Comparison of GCM climate feedback parameters for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour plus lapse rate (WV + LR) in units of* $W\ m^{-2}\ °C^{-1}$*. 'ALL' represents the sum of all feedbacks. Results are taken from Colman (2003a; blue, black), Soden and Held (2006; red) and Winton (2006a; green). Closed blue and open black symbols from Colman (2003a) represent calculations determined using the partial radiative perturbation (PRP) and the radiative-convective method (RCM) approaches respectively. Crosses represent the water vapour feedback computed for each model from Soden and Held (2006) assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks from Soden and Held (2006).*

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[19] Note that 'negative' refers to the effect of the feedback on the system, *not* on the desirability of the outcome. For the climate system, negative ones tend to be helpful and the positive ones unfortunate.

Modelled Climate Sensitivity

The sensitivity of the climate is the temperature rise that can be expected at thermal equilibrium[20] for a doubling of CO_2. This has been assessed by various studies, creating probability distributions. It is clear that there is a very wide range of expected assumptions, with radically different prognoses for the future of the climate.

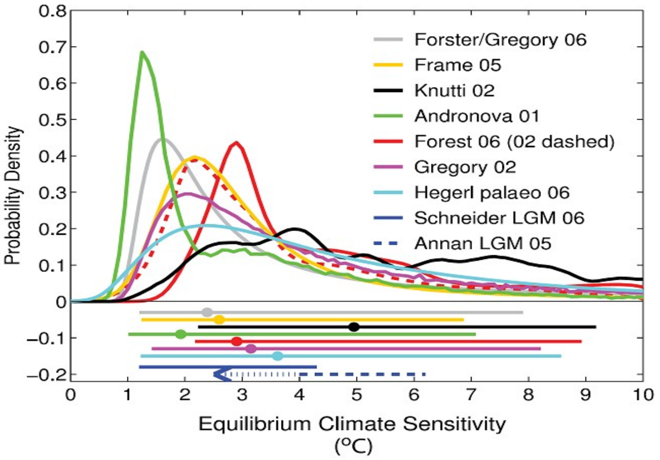

Figure 9.20. *Comparison between different estimates of the PDF (or relative likelihood) for ECS (°C). All PDFs/likelihoods have been scaled to integrate to unity between 0°C and 10°C ECS. The bars show the respective 5 to 95% ranges, dots the median estimate. The PDFs/likelihoods based on instrumental data are from Andronova and Schlesinger (2001), Forest et al. (2002; dashed line, considering anthropogenic forcings only), Forest et al. (2006; solid, anthropogenic and natural forcings), Gregory et al. (2002a), Knutti et al. (2002), Frame et al. (2005), and Forster and Gregory (2006), transformed to a uniform prior distribution in ECS using the method after Frame et al. (2005). Hegerl et al. (2006a) is based on multiple palaeoclimatic reconstructions of NH mean temperatures over the last 700 years. Also shown are the 5 to 95% approximate ranges for two estimates from the LGM (dashed, Annan et al., 2005; solid, Schneider von Deimling et al., 2006) which are based on models with different structural properties. Note that ranges extending beyond the published range in Annan et al. (2005), and beyond that sampled by the climate model used there, are indicated by dots and an arrow, since Annan et al. only provide an upper limit. For details of the likelihood estimates, see Table 9.3. After Hegerl et al. (2006a).*

All the studies seem to agree that the sensitivity is more than 1 Celsius and less than 9 Celsius! These are quite different! A sensitivity of 9 Celsius would be a guaranteed catastrophe for mankind and the existing biosphere, **unless we can get concentrations down to pre-industrial levels**. A sensitivity of 1 Celsius would mean that there is less urgency for tackling climate change, although **we might still want to stabilize Carbon Dioxide concentrations quickly, to prevent widespread ocean acidification**.[21]

The reason it is so difficult to constrain the climate sensitivity is shown on graph (c) below. With higher climate sensitivities, there is a greater lag, making it difficult to tell whether a temperature observation is associated with a low sensitivity and a small lag or a large sensitivity and a large lag.

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[20] Some may say that the earth is a chaotic system and not a system in equilibrium. This fails to note that the Earth, despite fluctuations, nevertheless has had a reasonably well defined *climate* over periods of thousands of years. Another might be that the Earth may never settle down; once pushed by some perturbation, it will continue to evolve, increasing in temperature, without further perturbation. There are some arguments for this view and they tend to argue for a high climate sensitivity and/or a long lag.

[21] If this reason is viewed as inadequate there are economic, geopolitical, and safety issues associated with fossil fuel extraction and the depletion of gas and oil reserves, which nevertheless motivate getting off fossil fuels. One way to do this is a carbon tax; this is a relatively efficient tax, so for independent economic reasons we may wish to use this as a source of government revenue. It's possible that none of these arguments convince you; but nevertheless, I would argue that the balance of benefits opposed to risks suits action of this type.

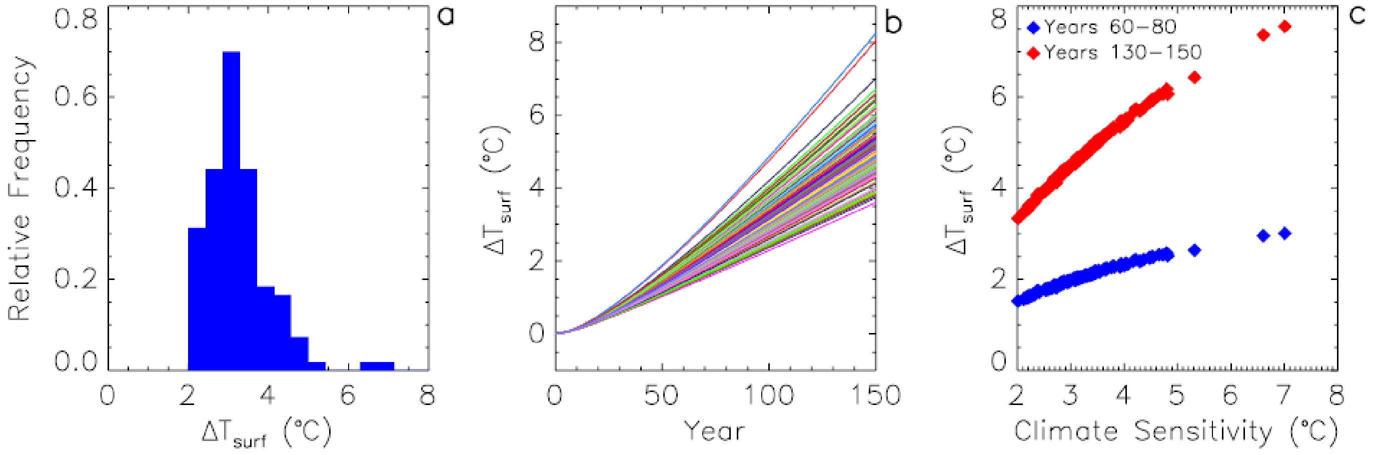


Fig. 10 **a** The frequency distribution of 2 × CO_2 equilibrium climate sensitivity, diagnosed from the 129 member perturbed physics slab model ensemble. **b** Plume of global surface temperature responses to a 1% increase in CO_2 concentration predicted by the EBM, using feedbacks diagnosed from a. **c** EBM transfer function between climate sensitivity and global surface temperature warming, for decades 60–80 (*blue curve*) and 130–150 (*red curve*), for a 1% increase in CO_2 concentration (i.e., two times and four times pre-industrial CO_2 concentrations, respectively)

Additional Positive Feedbacks & 'Equilibrium Climate Response'

Various potential positive feedback systems have been identified for the earth. For example:

- The melting of ice leads to a change in the colour of the earth's surface from a reflective white, to black, which absorbs more heat.
- Biological systems cannot cope with temperatures above a certain point, nor if temperatures change rapidly; release of biologically sequestered carbon therefore appears likely.
- Global warming may cause the collapse of rainforest ecosystems already ravaged by deforestation, releasing much stored CO_2 (Cox et al. 2004).
- There are large stores of permafrost in Siberia. This permafrost may melt releasing methane (a greenhouse gas); similarly there are further sources of methane on the sea floor(Burroughs 2001).
- Whilst moderate climate change (e.g. 1°C) therefore may be counteracted by various natural systems, large climate change (>2°C) may well be dangerous.

It should be noted that the main climate models **do not include all of these effects.** Therefore it has been suggested (Bettis 2009) that we should use a new term, *Equilibrium Climate Response*, to refer to the whole Earth-system response to the human input of greenhouse gases.

Towards a Conservative Estimate for the Equilibrium Climate Responses

Conservative means two different things 'not speculative' and 'playing safe':

- A 'non-speculative' assumption from the point of view of science might be 'reasonable' or 'mid-range'; this in a sense is a lower band: 'the sensitivity could be higher but we don't know that for sure'.
- A 'playing safe ' assumption from the point of view of a proper approach to action; in this case either the 'Prudent' or 'Risk-Averse' assumptions seem to be more valid.

I will label different assumptions according to this definition, below:

How Sensitive Is The Climate?

The following table gives some plausible numbers for the sensitivity of the climate.

Scenario	**Climate Sensitivity (committed temperature rise at 550ppmCO2 e)**	**Climate Sensitivity (KW^{-1}m^{2})**	**Feedback Assumption / Comments**	**As Scientific Scenario, how plausible is this?**	**RF under 2C**	**Stabilization Level of GHGs to avoid equilibrium temperature rise of 2 Celsius above preindustrial *(time reached)***	**Actions Needed**	**As a 'certainty equivalent' assumption to guide action how prudent is this?**
Reasonable[22]	2.2ºC	0.6	IPCC but with assumption of zero cloud feedback. Most likely short-term sensitivity based on current observations – but ignores possible positive feedback?	Plausible, and consistent with observations.	3.33	520ppmCO2^{e} *(reached by 2035 at current rate)*[23]	~50% global reduction by 2050 (~80% reduction in developed countries – cap and trade?)	Very risky; >50% chance of failure. Significant >5% risk of catastrophic (>5) outcome
Mid-range (IPCC)[24]	3ºC	0.75	Water Vapour + Lapse Rate + Albedo + Clouds(Assumed Positive)[25]	'Best guess' from IPCC models; [26]	2.67	460ppmCO2^{e} (*reached by 2015 at current rate*)[27]	Immediate carbon tax of £100/tCO$_2$ Carbon-free energy by 2030 *or* halt deforestation	Risky; However balance between what is feasible and the risks taken?
Prudent Assumption	3.7ºC	1	Mid-range-IPCC plus positive carbon cycle feedback (Cox & Scheffer 2005)	Plausible if best guess IPCC assumption is augmented by carbon cycle feedback.	2	400[28]	Immediate carbon tax of £100/tCO$_2$; 100% Carbon-free energy by 2030 *and* halt deforestation	Still faces risk; Current effects (e.g. ice melt) may still persist, potentially seeding long-term effects.
Risk-averse Assumption	6ºC	1.5	Full-system effects including interacting positive feedbacks from ice-albedo, methane release, and carbon cycle; (Hansen 2008)	Plausible if feedbacks are positive and interact. Consistent with paleoclimatic data	1.33	350[29]	Immediate carbon tax >£100/tCO$_2$; 100% Carbon-Free Energy by 2030; Increase in forest size; (Plus: Capture of CO^2 from Air? Geo engineering?)	Mostly Safe, avoids seeding catastrophic effects.
Safe						280	Stop Using Fossil Fuels Reforest the Globe	Safe

---

22 'Reasonable' assumption. This is the IPCC result but with an adjustment to assume zero cloud feedback rather than a net-positive cloud feedback, giving a sensitivity of 0.6Wm^{-2}K^{-1}. Consistent with observations, under the assumption of small lags (low heat capacity) and low aerosol albedo effects.

23 Taking into account Carbon Dioxide only, 520ppm CO$_2$ only would be reached around 2050.

24 Consistent IPCC midrange; also output with Hansen model.

25 i.e. cloud feedback assumed to be positive, an assumption which is contested by some scientists; although see Houghton for a rebuttal of Lindzen's claims.

26 Cloud feedback assumption shaky?

27 Taking into account Carbon Dioxide only, 460ppm CO$_2$ only would be reached around 2030.

28 Taking into account Carbon Dioxide only, 400ppm CO$_2$ would be reached around 2020.

29 We have already passed this concentration, even including Carbon Dioxide only. It may be feasible if the world moves to a zero carbon economy and forests around the world are regenerated.

The Carbon Cycle and Ocean Acidification

By burning coal, oil, and gas on an enormous scale, destroying forests and using intensive agriculture, we are polluting the atmosphere about seven times faster than oceans can remove the pollution.

Introduction

What is Carbon Dioxide?

Carbon Dioxide (CO_2) is the most important greenhouse gas responsible for causing global warming, and is the focus of this section. CO_2 is emitted when we burn fossil fuels such as *coal, oil and natural gas*. Fossil fuels are the remains of plant and animal life laid down over millions of years which at present rates will be used up over the course of a few centuries. Fossil fuels contain *carbon*, which combines with oxygen in the air to produce carbon dioxide when burnt.

Stocks of Carbon

Where is the carbon located - and what form does it take?

- Fossil Fuels: stores of fossilized plants and animals in coal, oil, gas and peat - pure carbon and hydrocarbons - compounds containing carbon and hydrogen.
- Atmosphere: thin as a shell across the earth containing small quantities of carbon dioxide.
- Land Biomass (vegetation, soil and detritus): containing plants, soils and other biomass - cellulose and other compounds containing carbon hydrogen and oxygen.
- Oceans - carbon dioxide, which forms *carbonic acid* in water; carbonate and bicarbonate ions. Split into:
  - ○ Shallow Oceans – In direct contact with the atmosphere
  - ○ Intermediate & Deep oceans –
- Rocks: such as limestone - primarily calcium carbonate ($CaCO_3$).

The total carbon content in Gigatonnes of Carbon (GtC) is shown in the Figure 7.3 from the latest IPCC report.

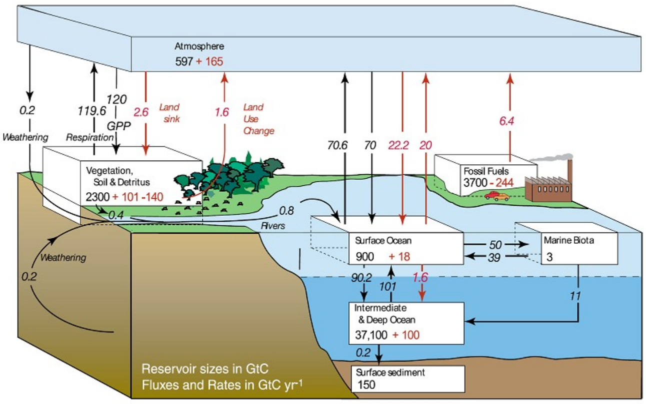
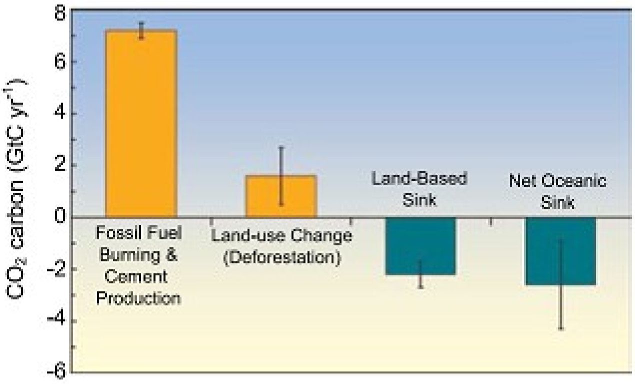
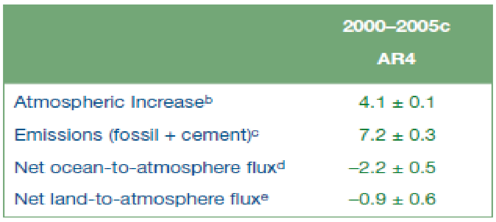


Figure 7.3. *The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr^{-1}: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004a). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr^{-1} for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994.*

Flows of Carbon

Fossil Fuels to Atmosphere





	2000–2005c AR4
Atmospheric Increase[b]	4.1 ± 0.1
Emissions (fossil + cement)[c]	7.2 ± 0.3
Net ocean-to-atmosphere flux[d]	−2.2 ± 0.5
Net land-to-atmosphere flux[e]	−0.9 ± 0.6

How much carbon do we release through the burning of fossil fuels?
We burn *7.2 billion tonnes of carbon per year (GtC/yr)* in fossil fuels[30], (IPCC 2007c, p.3). To put this in context, this is equivalent to a *cubic mile of oil* (Goldstein & Sweet 2007), or to *a forest the size of Western Europe*[31].

Land Biomass to and from Atmosphere

How much carbon do we release through the burning of forests and other land use processes?
By processes such as deforestation, we burn around 1.6 billion tonnes of carbon per year (GtC/yr) in trees and other land biomass[32].

How much carbon does the land take in?
The land absorbs around 2.7 billion tonnes of carbon per year (GtC/yr)[33].

What is the overall effect?
The net flow (sum of all the positive and negative flows) of 0.8 billion tonnes of carbon per year (GtC/yr) into the atmosphere[34].

What is the overall prognosis for the land biosphere?
The long term fate of the land biosphere will depend on multiple processes, such as land use and global warming. As the globe warms, carbon will be released from the land biosphere. Since carbon stored in the biosphere is there only temporarily, it may be best to consider it as a net sink of greenhouse gases.

How should we consider the flows to the land?
The flow to the forests cannot be considered sustainable on a human time scale of a century (since although carbon is taken from the atmosphere to the land with CO_2 fertilization; this flow may reverse with global heating).

Since the flow of carbon to the land biosphere is influenced by human activity, it would be best to consider the land biosphere as primarily a stock. We should look at ways of permanently increasing the total amount of carbon stored in the biosphere, by preventing deforestation, leaving land to return to forest.

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[30] This amounts to 26 billion tonnes of CO_2 per year emitted into the atmosphere.

[31] Forests contain approximately 20 tonnes per hectare or 2000 tonnes per km$^{2;}$ our fossil fuel consumption (about 7 Gigatonnes of Carbon per year) is therefore equivalent to a forest about 3.5 million square kilometers (approximately the size of Western Europe) being burnt every year.

[32] Land use changes release around 5.9 billion tonnes of CO_2 per year.

[33] Land takes in about 9.5 billion tonnes of CO_2 per year.

[34] Overall, there is a net sequestration of 3.6 billion tonnes of CO_2 per year

Atmosphere to Oceans

How do the oceans sequester CO_2?

The upper oceans *dissolve* CO_2 in water. The top of the ocean (the 'mixed layer') is in instant equilibrium with the atmosphere; however, it can only absorb a small amount of CO_2.

Chemical Reactions

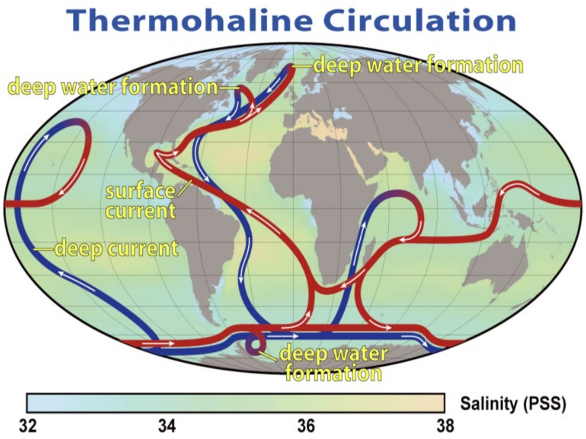
In dissolving CO_2, the upper oceans become less alkali (a process known as 'ocean acidification'):
$CO_{2\,(g)}+H_2O \leftrightarrow CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_{3\,(aq)} \leftrightarrow HCO_{3\,(aq)}^{-} + H^{+}_{(aq)}$

The oceans can absorb quite a lot of CO_2 because of the action of the carbonate/bicarbonate 'buffer': $H_2CO_3 + CO_3^{2-} \leftrightarrow 2HCO_3^{-}$ and so the total stock of carbon stored in the ocean is quite large.

The Solubility Pump(Takahashi et al. 1993, p.844)

It is the flow from the upper oceans to the lower oceans that is the basic determinant of the amount of CO_2 sequestered by the oceans. This is the 'rate limiting step', to use the chemistry jargon.

The solubility of CO_2 in cold water is twice that of warm water (about 3kg/m^3 at 4°C compared to 1.45 kg/m^3 at 25°C)[35]. As water moves from the tropics to the poles it therefore absorbs more CO_2. When this water falls in the thermohaline circulation (THC) it therefore takes the CO_2 with it. Before industrialization, the downwelling of the CO_2 was balanced by upwelling in the tropics. However, now the water that is falling has a higher concentration than that which is upwelling. This is because the conveyor-belt takes a few thousand years to fully turn (see figure right).



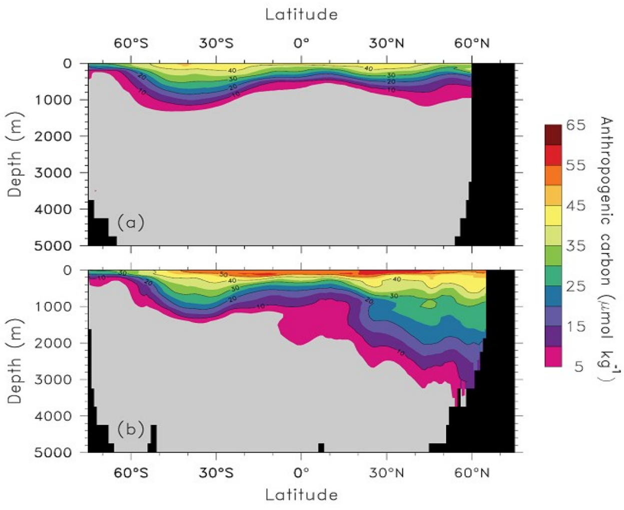


Figure 5.11. *Mean concentration of anthropogenic carbon as of 1994 in μmol kg–1 from Sabine et al. (2004b) averaged over (a) the Pacific and Indian Oceans and (b) the Atlantic Ocean. The calculation of anthropogenic carbon is described in the caption of Figure 5.10 and in the text (Section 5.4).*

How Sustainable is the Solubility Pump?

Since downwelling is proportional to the current atmospheric concentration of CO_2 and upwelling proportional to the preindustrial concentration, the rate of the thermohaline solubility pump is likely to be approximately equal to: (Current Concentration of CO_2) – (Preindustrial Concentration of CO_2)

Flows

Flows of CO_2 *into the atmosphere*	*Fossil Fuel Combustion*	*Burning Forests & Soil carbon release*	*Ocean Upwelling*	*Limestone Creation*
Flow	From Fossil Fuels	From Land biomass	From deep oceans (CO_2)	From Ocean

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[35] 1.45 g/L = 1.45 kg/m^3 since 1000L = 1 m^3

	(Hydrocarbons) to Atmosphere (CO_2)	(organic Carbon) to Atmosphere (CO_2)	to surface (CO_2)	(Bicarbonate) to Rock & Ocean ($CaCO_3$ plus CO_2)
Explanation	Extracting coal oil and gas; combustion in air	Burning of forests releases carbon; additionally, soils release carbon through natural processes (may accelerate with global warming)	Deep ocean water, rich in CO2 up wells in tropics, warms and releases CO2; however because it is 'old' it contains less CO2 that that which downwells.	By organisms dropping to sea floor
Quantity of Flow	+7GtC/year	(+ PreindustrialY_1[36]) +2GtC/year	(+ PreindustrialX_1)[37]	+0.2GtC/year[38]
Feedback (Negative counteracting climate change; positive accentuating it)	Positive (air conditioning demand; war) and Negative (heating demand)	Positive (increased temperatures lead to increased respiration in soils and increased dessication/burning of forests and peat)	Positive (increase in temperature could cause stratification of ocean and shutdown of thermohaline circulation)	Negative (acidification reduces creation of limestone)
Flows of CO_2 *out of the atmosphere*	*Fossil Fuel Creation*	*Afforestation and Soil carbon sequestration*	*Ocean Downwelling*	*Limestone Weathering*
Flow	From atmosphere or oceans (CO_2) to rock (hydrocarbons)	From Atmosphere (CO_2) to Land Biomass (organic Carbon)	From surface (CO_2) to deep oceans (CO_2)	From Rock & Ocean (CO_2 plus $CaCO_3$) to Ocean (Bicarbonate)
Explanation	Microorganisms dropping to sea floor; laying down of new peat; biochar.	Growth of plants; further afforestation or reforestation	Because downwelling water is cold, it contains a lot of CO_2; additionally, because it is recently mixed it contains more CO_2	In land rocks or on seabed
Quantity of Flow	Less (in absolute terms) than -0.1GtC/year	(- PreindustrialY_2) - 3GtC/yr	(- PreindustrialX_2) - 2GtC/yr	-0.2GtC/year
Feedback (Negative counteracting cc; positive accentuating it)	Slightly positive	Negative (CO_2 fertilization)		Negative (acidification increases weathering)

Additional flows between the shallow and deep ocean	*Organic Matter Forming, Dropping and Rotting*	*Net Upwards Diffusion & Bubbling*	*Limestone Forming, Dropping and Redissolving*
Effective Flow	CO_2 from shallow ocean ($CO_2 \rightarrow$ organic carbon plus oxygen) to deep ocean; (organic carbon $\rightarrow$ CO_2 minus oxygen); Oxygen in reverse direction	CO_2 from deep oceans to shallow oceans	Bicarbonate from shallow oceans ($2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$) to deep oceans ($CaCO_3 + CO_2 + H_2O \rightarrow 2HCO_3^-$); CO_2 from deep oceans to shallow oceans.
Explanation	Part of 'biological pump'???	Simple diffusion or CO_2 bubbles rising	Part of 'biological pump'???
Quantity of Flow	+PreindustrialX_3	+PreindustrialX_5	-PreindustrialX_4
Feedback	Negative (Fertilization) or Positive (Acidification)	Positive? (Increased windiness increases diffusion rate)	Negative (acidification reduces creation of limestone)

Overall Effects

How much do our emissions raise the concentration in the atmosphere?

With approximately half the emissions of carbon dioxide taken up by the oceans and land, the net flow into the atmosphere is approximately 4.1GtC or (15GtCO_2) (IPCC 2007a Chapter 10). One

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[36] Preindustrial land biomass flows in approximate balance i.e.: $Y_1 = Y_2$

[37] Preindustrial ocean flows in approximate balance i.e.: $X_1 + X_3 + X_5 = X_2 + X_4$

[38] CO_2 only. Also same amount of $CaCO_3$; so total flow of Carbon from bicarbonate to CO_2 and $CaCO_3$ is twice this figure.

gigatonne of CO_2 is equivalent to 0.128ppmv CO_2. So our current net CO_2 emissions flow (15 Gigatonnes of Carbon Dioxide per year) corresponds to the present growth rate of CO_2 in the atmosphere (2ppm per year). Overall, the atmosphere concentration of CO_2 has risen from 280 ppm (pre-industrial times) to 380ppm (recent measurement) (Engineering Toolbox 2008).

What level of emissions might be sustainable?

What is the level of emissions that would allow concentrations of carbon dioxide in the Earth's atmosphere to stabilise? About 7 billion tonnes of CO_2 (–2.2 ± 0.5 GtC) (IPCC 2007a, p.516) are mixed by the oceans each year – approximately one tonne of CO_2 per person on earth(CIA 2008). This is the maximum that we can emit in a sustainable way: globally (2004) we are six times over budget. We need to get down to about 1 tonne of CO_2 per person per year.

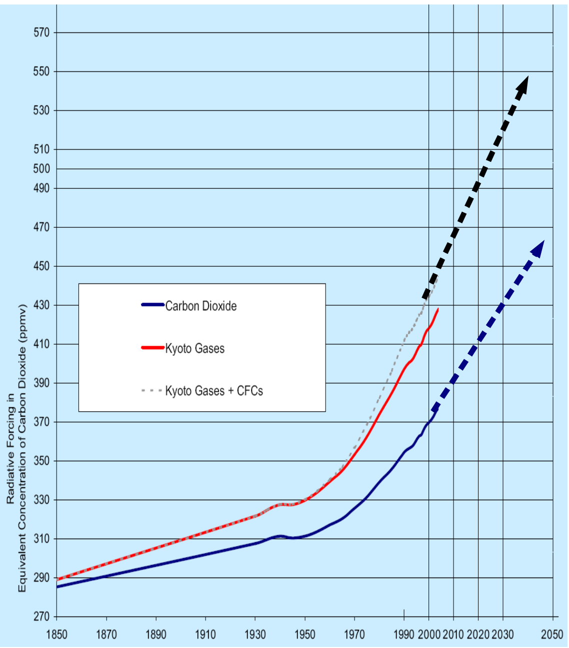
Conclusion

To stabilize global concentrations of carbon dioxide, CO_2 emissions from fossil fuels must fall to approximately 7 Gigatonnes of CO_2 per year (2 Gigatonnes of Carbon per year).

Observed Greenhouse Gas Concentrations and Global Warming

Greenhouse Gas Concentrations

Current atmospheric concentrations of greenhouse gases are equivalent to 383ppm CO_2 only or 430ppm CO_2^e (Tans 2010), rising at about 3ppmCO2e/year. The *rate of growth of emissions is still increasing*, as shown by countries such as China (building 2 coal power stations per week).

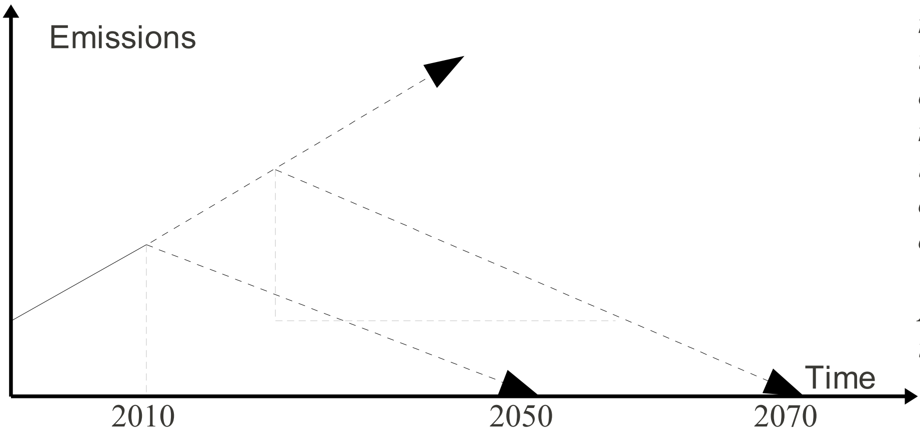


Source: Adopted from Stern (2006)

Expected Temperature Rises

Temperature rises of +0.7C above the pre-industrial level have been observed already. Some of the warming effect is being masked at present, but even at current levels we are seeing very dramatic warming at the poles. with approximately the same temperature rises in the pipeline.

In order to have a 50/50 chance of stabilizing global average temperatures at 2°C above the pre-industrial level, greenhouse gas concentrations have to be stabilized at approximately current levels. A rapid reduction in global greenhouse gas emissions can have a high chance of achieving this 2 Celsius target.



Delaying emissions reductions for a decade implies both additional emissions and a longer time needed to reduce emissions to sustainable levels; both contributing to increased cumulative emissions.

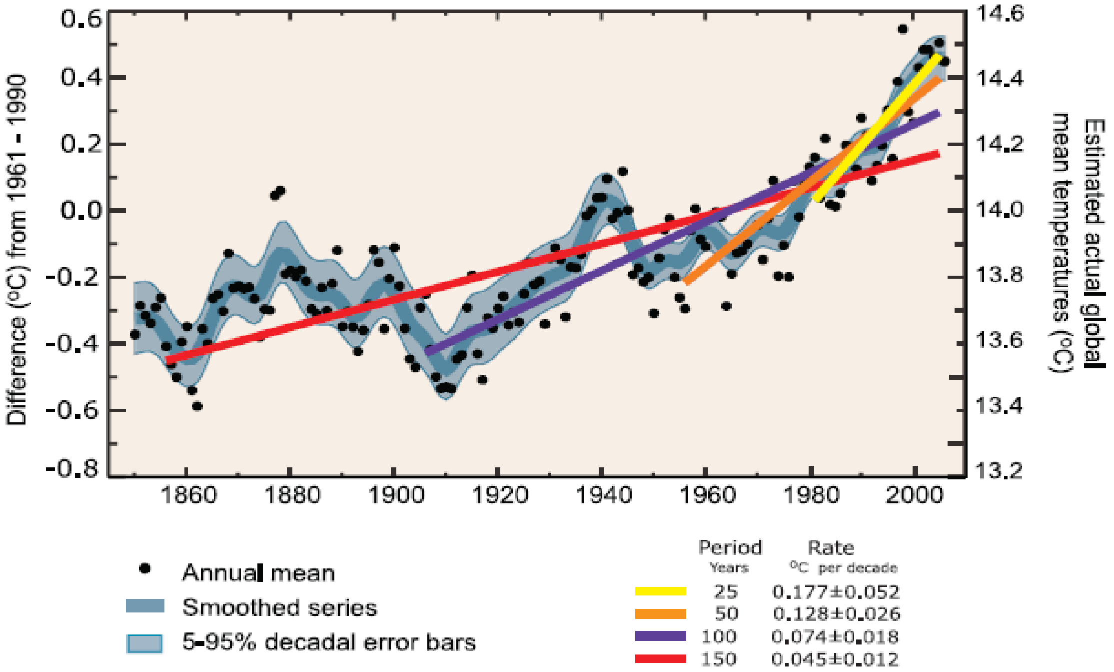
A twenty year delay (figure) induces approximately 1 Celsius more warming.

Doubling (550ppm CO_2e) will lead to a temperature rise of 3°C above the preindustrial from fast feedbacks alone; potentially 6°C if 'slow feedbacks' are included, (Hansen et al. 2008)

Quadrupling (1100ppm CO_2e) by end of century would lead to at least 6ºC of warming.

Observations of Temperature Rise

The following graph gives the global average temperature according the the IPCC. **The trend over the last 25 years has been an increase in global temperatures of 0.18ºC per decade.**



Assessing the IPCC Climate Models

One simple way to assess the models we have of the climate is to compare their predictions to what has been observed (see the predictions of the previous IPCC assessment reports, along with observations of the global temperature). It can be seen that the observations of global average temperature are on the lower bound of the First Assessment Report (FAR); the upper side of the range of the Second Assessment Report (SAR); and approximately consistent with the Third Assessment Report (TAR).

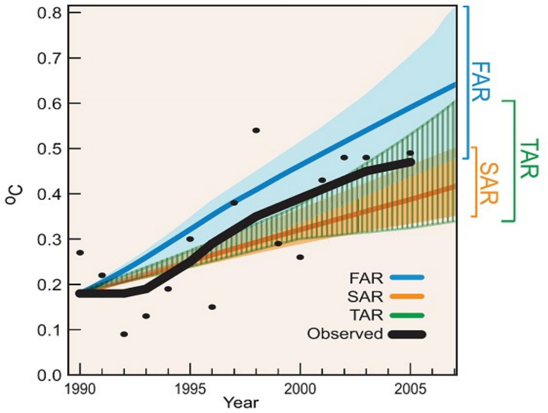


Figure 1.1. *Yearly global average surface temperature (Brohan et al., 2006), relative to the mean 1961 to 1990 values, and as projected in the FAR (IPCC, 1990), SAR (IPCC, 1996) and TAR (IPCC, 2001a). The 'best estimate' model projections from the FAR and SAR are in solid lines with their range of estimated projections shown by the shaded areas. The TAR did not have 'best estimate' model projections but rather a range of projections. Annual mean observations (Section 3.2) are depicted by black circles and the thick black line shows decadal variations obtained by smoothing the time series using a 13-point filter.*

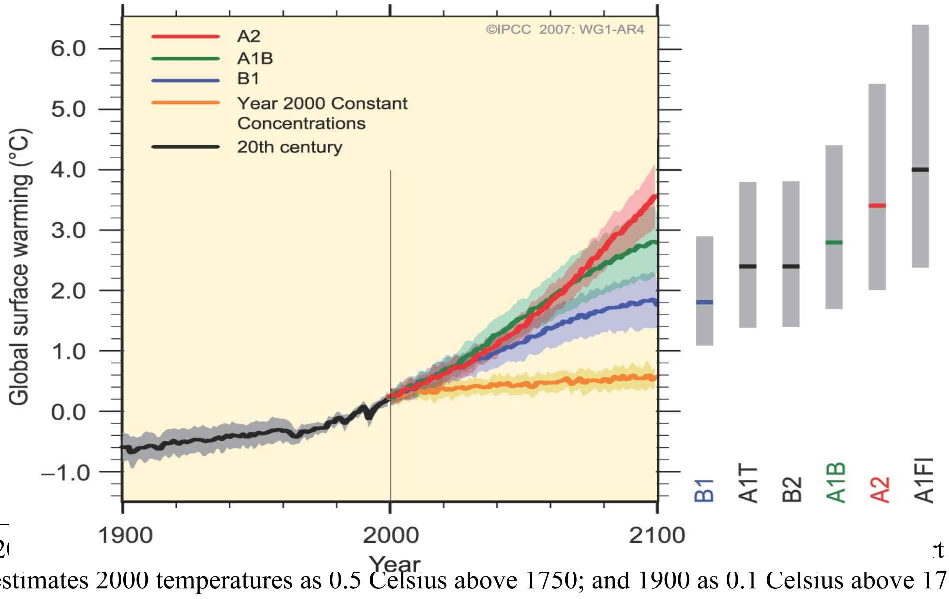
Temperature Definitions

There are unfortunately, a number of temperature definitions in place. The following table deals with the main standards in use.[39]

Time Period	**Global Mean Surface Temperature**	**Level above Pre-industrial temperature**[40]	**Where Used?**
1750-1850	~13.7	~0	Stern review impacts EU '2C target'.
1861-1900'	13.7	0	Sometimes also defined as the 'Pre-industrial' temperature
1900	13.7	0.1	-
1901-1950			IPCC AR4 WG1 Comparing model with past
1961-1990	14	0.3	**Temperature Anomalies**; AR4 WG1 p6 SPM.3
1980-1999	14.2	0.5	**IPCC Future Predictions & Impacts**; e.g. AR4 WG1 p14 SPM.5[41]
2000	14.45	0.75	Hansen (2006) '1C target'

Expected Transient Temperature Rise

The following graph (IPCC 2007a) shows the observed and predicted temperature rise over the 20th and 21st Centuries. Note that this shows transient temperature rather than the total temperature commitment. The yellow curve shows the temperature rises that would result if we kept GHG concentrations fixed at 2000 levels.



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[39] IPCC (2 … t (TAR) estimations, which estimates 2000 temperatures as 0.5 Celsius above 1750; and 1900 as 0.1 Celsius above 1750 (See Stern Review p58)

[40] Defined as the temperature between 1861-1900

[41] AR4 WG1 Technical Summary p69 TS.26 uses 1990 temperature.

The Impacts of Climate Change

The degree of climate change is usually measured as the overall change in global temperatures relative to long term norms. Local temperatures may rise more than the global average since the land will warm faster than the oceans and polar regions will warm faster than the tropics. The effects of climate change are very serious for both human civilization and the natural world, and include:

Heat waves, Droughts and Desertification

With climate change, there will be increased frequency of heat waves and droughts in already hot or dry areas. The tropics are likely to expand, meaning that the dry zones around North Africa and Mexico will spread north and in Southern Africa and Australia will move south, leading to large (over 30%) reductions in precipitation for the Mediterranean countries (Spain, Italy, Greece). Changes in precipitation and temperature lead to increased water and food stress, famine, refugees, and conflict.

Accelerated Ice Melt and Sea Level Rise

Sea level is likely to rise by between a few inches to a few metres over a century, in a slow but accelerating process. The melting of the Greenland or West Antarctic ice sheets over centuries would each raise the sea level by 6.5m each (13m in total), inundating many small islands and coastal cities such as London[42].

Diseases

Increased disease frequency as malaria and other pathogens spread to other areas. It is possible that rapid changes in temperature patterns and the disruption of ecosystems could lead to the emergence of new diseases.

Degrading or Collapse of Ecosystems

There will be widespread changes in ecosystems including the collapse of the coral reefs (probably inevitable even with moderate climate change).

Carbon-Sink-to-Source Transition

Possible collapse of the Amazon Rainforest leading to further CO_2 emissions. This is the land ecosystem with the greatest biodiversity and alone would constitute a Carbon cycle feedback of more than 100ppm of CO2 (Cox et al. 2000) (Met Office 2000)

Methane-Sink-to-Source Transition

There are already some reports (Pearce 2006) of release of methane from the frozen permafrost. It is possible that, for large rises, the massive stores of Methane Clathrate on the ocean bed might be released[43]. Such releases have been implicated in the Paleocene-Eocene Thermal Maximum (seen 50 million years ago) and the end-Permian extinction in the so-called 'Clathrate gun' hypothesis (Dickens et al. 1995), (Dickens et al. 1997), (Renssen et al. 2004).

Catastrophic 'Non-linear' Events

An increased temperature might cause the collapse of the global heat circulation system[44].

---

[42] If the East Antarctic ice sheet melted, the rise would be 84m; (this *seems* unlikely, although paleoclimatic evidence (Hansen et al. 2008) suggests that it is possible for CO_2 concentrations of 550ppm or more).

[43] Methane stocks at risk (Stern 2006):

- Permafrost & Wetlands 3000GtCO_2 equivalent to 300ppm CO_2^e over a century or less
- Methane Hydrates: 3000GtCO_2? equivalent to a further 300ppm CO_2e

[44] The flow of cold melt water from the Arctic may interrupt the 'gulf stream' part of the heat conveyor that transports energy from the tropics to temperate areas. This will cause Europe and in particular Northwest Europe to become locally much (perhaps 5C) colder, and maybe to have a climate more similar to Newfoundland, Canada. Tropical

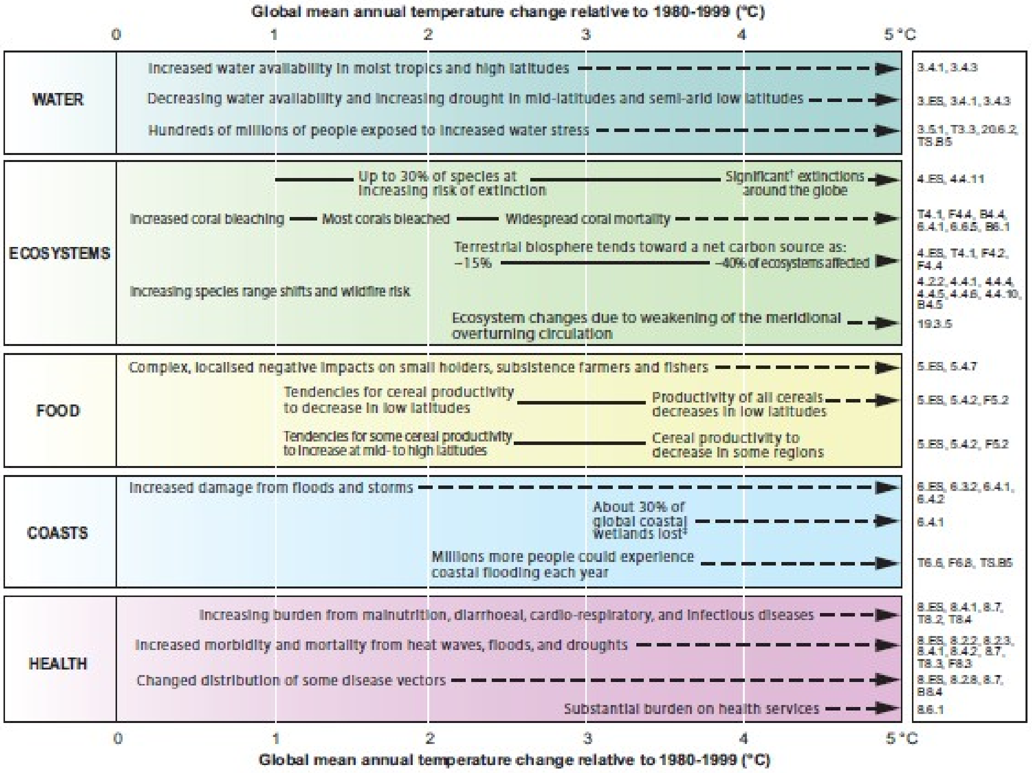
Completely unforeseen effects cannot be ruled out.

Acidification of Oceans

In addition to the effect of carbon dioxide on global temperatures, it directly effects ocean pH, leading to serious effects on ocean micro-organisms for atmospheric concentrations of around 550ppm CO_2.

Quantifying Impacts

The impacts of climate change are described in the IPCC report (IPCC 2007b) and 'Avoiding Dangerous Climate Change' (Warren 2006). An excellent popular account based on 500 scientific papers is available (Lynas 2007)[45]. The impacts and economic costs of climate change are also reviewed in the Stern Review (Stern 2006).



† Significant is defined here as more than 40%.

‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure SPM.2. *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.8]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Endbox 3). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the Assessment. Sources are given in the right-hand column of the Table. Confidence levels for all statements are high.*

Discussion: What is the Optimal Earth Temperature?

One of the interesting features of the universe we are in is that the value of fundamental constants in the scientific laws that govern it appear in some sense 'just right' to create a complex and interesting universe. To the extent to which the laws of nature were different the universe might not work how it does now; or might not really work at all. The same appears to be true for life. Life as

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regions such as West Africa may become even warmer.

[45] Lynas (2007) is not *itself* peer reviewed, but remarkable as a *review* of the peer-reviewed literature. A summary is available here http://tinyurl.com/cqbtrc A review (Rahmstorf 2007) concludes that Lynas' reading of the scientific literature is largely accurate, although credible risks are sometimes made out to be certainties.

we know it depends for example on being able to create long chains of carbon atoms in molecules essential for life, for example DNA.

The same could be said about planet Earth and it's habitability. If the Earth were slightly further from the sun, it might have stayed forever frozen; a little closer and the water might have boiled, created a hothouse greenhouse effect and making complex life difficult. The earth's temperature can also be viewed as near-optimal for the plants and animals (including mankind) on it's surface.

From an objective perspective, it can be said that life has evolved and adapted within a particular environment. The transition from ape to modern man seems to have taken place mostly in Africa, over the last million years. After leaving Africa our ancestors hunted woolly mammoths to extinction, tens of thousands of years ago. Living things have evolved to suit a particular environment and, as James Lovelock has pointed out, can be said to have influenced that environment in turn, for example by sequestering carbon dioxide from the atmosphere in the form of fossil fuels. Lovelock has recently argued that 'Gaia likes it cold' (Lovelock 2006) - biological temperature control mechanisms work better at a lower temperature.

Lovelock in addition argues that the earth regulates the temperature of the earth. One analogy he uses is 'Daisyworld'; such a world can regulate it's temperature. Biological and ecological systems show quite different behaviour to simple physical or chemical systems. Typical of biological systems is that they exhibit negative feedback up to some threshold, and positive feedback or catastrophic failure past this threshold.

Ethics and Economics

We have determined (section 1) that it is necessary to reduce global emissions to approximately 7 Gigatonnes of CO_2 to stabilize concentrations of CO_2. But how fast should we or could we get down to this level?

Should We Do Anything About Climate Change?

- Firstly, a question about the significance of future climate changes. This question 'Does the weather really matter' - the social implications of climate change has been dealt with in detail (Burroughs 2001). Climate change affects the poor more than the rich; and the natural world even more than the human world.
- Secondly, the questions as to whether we should care about them even if they do matter. Does the future matter?
- Thirdly, the significance of the natural world relative to human wants.

The best place to go for an overall review of the economics is still the Stern Review (Stern 2006), although the reader should be aware that the area of discount rates is not uncontroversial.

Here is a summary of what can be quantified and what cannot:

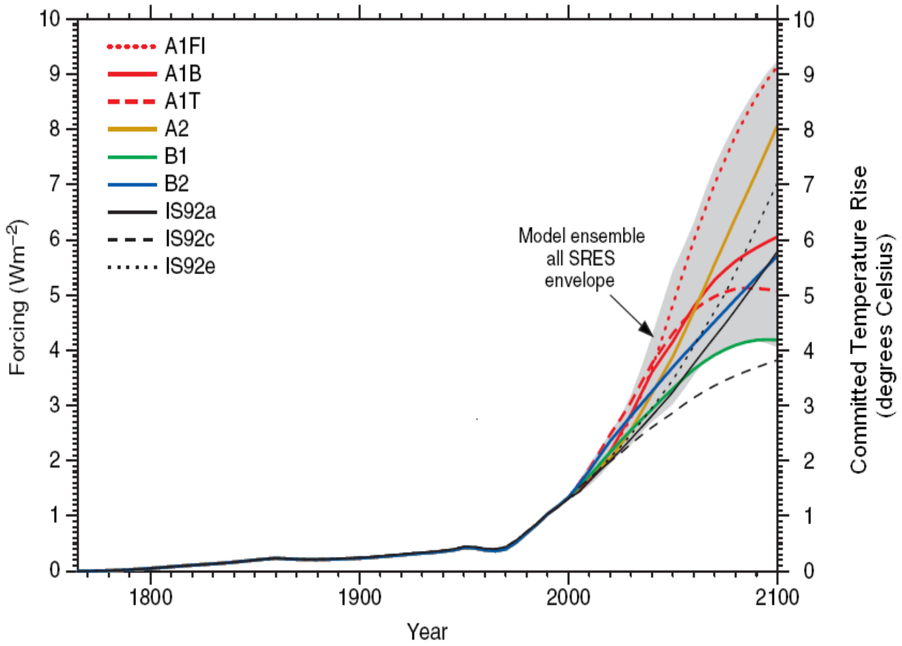
1. GDP losses from further climate change may amount to 5-20% of GDP (Stern 2006)
2. However, the 'insurance cost' of climate change may be dominant in our thinking: it may be rational to pay almost anything to insure against unbounded harm. (Weitzman 2008) (Weitzman 2007).
3. Stern doesn't include 'Societal Contingent Events' – Mass migration, water, food riots etc.
4. Societal change (is the response of society fragile – Easter Island, Sudan, etc. or robust?) (Diamond 2005)
5. Unexpected events – 'unknown unknowns' may not be taken into account (Diseases, weather etc.)
6. If in the future it is necessary to remove CO_2 from the atmosphere (Keith et al. 2006), wll anyone pay?

An interesting discussion of the ethical aspects of the Stern Review is available in Jaeger et al. (2008):

> “The Review has compared climate change to experiences of suffering like World War I. That war, however, hardly affected global GDP. The long-term damages to be expected from business-as-usual greenhouse gas emissions include loss of the coastal cities of the world over the next millennia. This would be an act of unprecedented barbarism, regardless of whether it would slow down economic growth or perhaps even accelerate it. Business leaders worried about climate change need to pay attention to the tensions between ethical and economic concerns.”

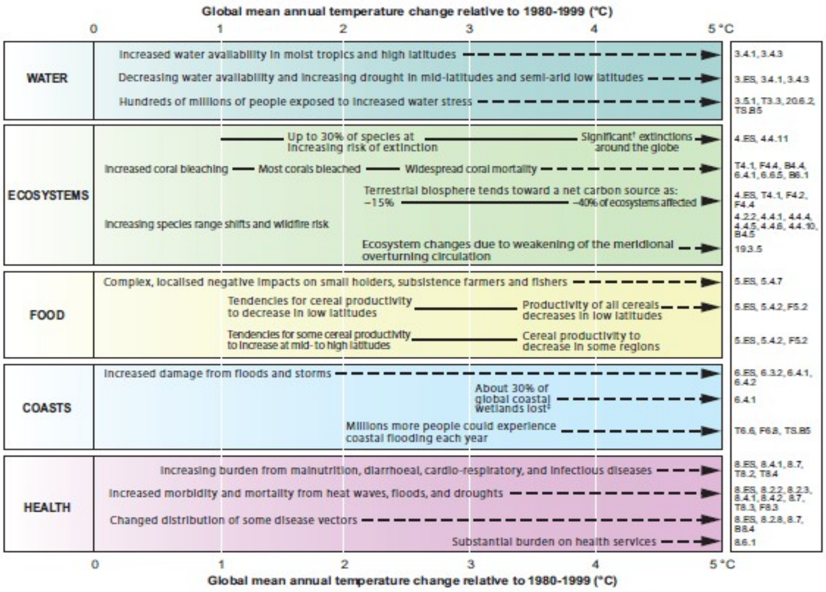
Global Warming Commitment[46]

Committed Temperature Rise



Assumes that temperature rises by 3.7degrees Celsius with a greenhouse gas concentration equivalent to 550ppm CO2 (doubling of pre-industrial levels)

Impacts



† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure SPM.2. *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.8]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Endbox 3). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the Assessment. Sources are given in the right-hand column of the Table. Confidence levels for all statements are high.*

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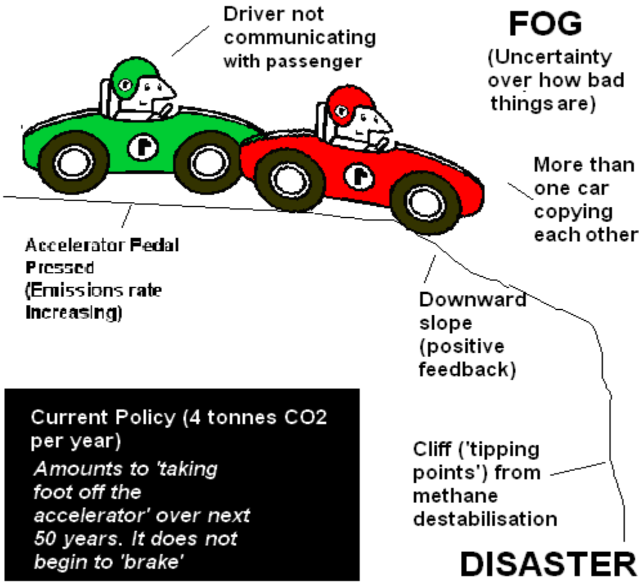
[46] Temperature commitment adopted from IPCC (2001) . Impacts from IPCC (2007b)

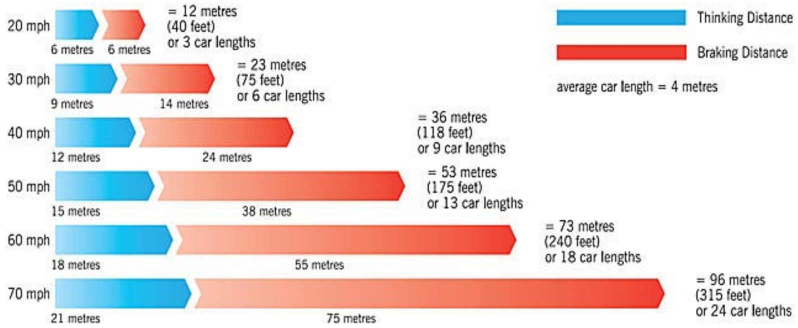
Discussion

“THE THINKING DISTANCE, BRAKING DISTANCE AND OVERALL STOPPING DISTANCE”



Climate change is a particularly difficult problem to solve. Usually, when society is faced with a serious problem, there will be people who have been seriously affected or damaged by the problem, and they will demand redress and reform. In the case of climate change, we have to think ahead to the most serious damages happening in the *future*. There is a lag of as much as 50 or 100 years between our policy or personal actions now and the full impacts and consequences of those actions.

It is a bit like the situation faced by drivers on a road. When we learn to drive, we are taught that there is a 'stopping distance'; it takes time to react to a stationary hazard and then further time for the car to stop. When faced with a stationary hazard ahead of us, it is not enough to wait until the car becomes damaged as it hits the stationary object; we have to *look ahead.* It's exactly the same with climate change.[47]



Thinking, Breaking & Stopping Distance for a Normal Car. Climate change has many lags which

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[47] One of these reasons is that the lag between changes to policy, which affect investment; the cumulative effect of investment affects emissions; the cumulative emissions affects the concentration of greenhouse gases in the atmosphere; and the concentration of greenhouse gases affects the cumulative temperature. Temperature takes time to adjust to any given concentration due to the thermal inertia of the oceans, and this raised temperature will lead to increased humidity and further increases in temperature. A higher temperature will lead to further increases in carbon and other greenhouse gases:

1. The main measure to deal with climate change are policy interventions such as carbon taxes and regulations (T). (Change in level of the accelerator). A constant escalation in policy is an averaged representation of multiple policy uncertainties and inertia.
2. Aggregate climate policy (e.g. carbon prices) (P) represents the cumulative effect of these interventions or tightening caps P=int(T). The level of Carbon Prices is related to the net increase or reduction in polluting assets (including the investments of lifestyle change).
3. The accumulation of investment decisions will affect the level of emissions(E)=int(I) (Speed)
4. The accumulation of emissions that determines the future or final concentration of greenhouse gases C=Int(E) in the atmosphere (Distance)
5. The level of greenhouse gases (which we hope will stabilize) determines the planetary heat imbalance. However, it takes time for the temperature to adjust, due to the thermal inertia of the oceans.
6. As the temperature increases, the humidity of the atmosphere will also increase. This will further increase the temperature (this is known as a 'fast feedback').
7. As the temperature further increases, the increased temperature will melt ice, and release stored carbon from the biosphere over a time-scale of a century or so (this is known as a 'slow feedback').

mean that we have to look ahead, quantifying the risks and timings to avoid serious danger.

Since most of the human impact and consequent political pressure will not take place until it is too late to avoid them; we need to find ways to think ahead and predict the future. In the case of the car, we look ahead and see the future, and we know individually from training or experience that we have to stop the car. However, collectively thinking ahead may be more difficult in novel situations; we may mostly look at what other people are doing. That leads to a collective 'tipping point' which will come when people start to take a problem seriously.

Certain groups in our society are able to look ahead with vision; the people building great infrastructure projects such as the sewers of London for example; others perceive dangers before others (e.g. Churchill warned about the dangers of Hitler in the 1930s). Strategic institutions in our society can manage risks. The people who maintain our defence forces defend us against foreseeable future risks. We need robust global defence against dangerous climate change; and the best form of defence is to avoid the problem altogether.

The difference in perspective between those who look ahead and those who do not may explain why there often appears so much shrillness in the debate over climate change, especially in the United States. Self-styled climate 'sceptics' argue that the evidence for existing climate change is limited and does not justify the rhetoric of 'a state of planetary emergency' (Gore). Few people, at least in the United States, seem to be affected directly to the level that justifies such a public outcry. Some even refuse to accept that we live on a planet kept warm by a greenhouse effect driven by carbon dioxide and a few other gases; and that by emitting the gases at current or increased levels, the global temperature will rise.

Many scientists and those who cross disciplines, by contrast, are asking a different question: what do we need to do now to avoid an unacceptably high risk of very damaging future changes to the climate? Trial and error is an unacceptable approach when there is no second planet to live on: if we mess up, we are stuffed. We need to understand the structure of the world and the future choices available to us and so take avoiding action in time.

We need to understand the capabilities of the planetary vehicle we are in, and take avoiding action to clear and present dangers facing us on the road ahead. Although dangers can sometimes seem far off, we also need to take account of the fantastic speed we are travelling.

With foresight and a bit of luck we can probably avoid the most serious impacts and risks of climate change. To do so, policies to drive a move to a zero carbon society need to be implemented soon across the world: in the new UK parliament, and with the United States administration.

Conclusions

It is well known that the temperature of Earth is significantly (IPCC 2007a, p.516) warmer than it would otherwise be due to a 'greenhouse effect' driven by Carbon Dioxide (CO_2) and other so called greenhouse gases (GHGs), a warming that is amplified by water vapour. Humans are now emitting carbon dioxide from burning fossil fuels, industrial and agricultural process and land use change at a rate about seven times faster than the oceans absorb it (see chapter 1).

The atmospheric concentration of CO2 is now higher than any time in the last 720,000 years (Augustin et al. 2004), and probably the last 22 million years (Cox et al. 2000). The concentration of other greenhouse gases is similarly elevated. In addition to the warming effect of CO2 in the atmosphere, the flow of carbon dioxide into the upper oceans is decreasing the alkalinity of the oceans, (an effect known as 'ocean acidification'), with potential effects on ocean ecosystems and the food chain.

There is strong evidence that the Earth’s surface has been warming up (including surface temperature records and the observation of glaciers worldwide (IPCC 2007a)). So far, the global temperature has risen by about 0.75°C above the long run average(IPCC 2007a; Chapter 3; Page 237). The latest report from the International Panel on Climate Change, summed up the global picture of observations in uncharacteristically bold language, asserting that “warming is unequivocal”.[48]

Up to 2100, global temperatures are likely to increase by an average of a further 1.5-6°C according to the collection of models assembled by the (IPCC 2007a) although the rise could be larger with positive feedbacks of various types (Cox et al. 2000) (Pope 2008). There is a lag of many decades between human behaviour and infrastructure, and the full impacts of that behaviour and infrastructure.

To avoid 'dangerous' climate change (which has been defined as a rise of more than 2ºC above the pre-industrial), we must take immediate action to convert to a near-zero emissions economy (chapter 2), with a 90% reduction in developed countries' carbon dioxide emissions by 2030[49]. If the UK took the necessary actions now, they could be widely copied in other parts of the world, such as the rest of Europe, North America, China, and India. I will argue later in this book that it is feasible to move quickly to a zero-carbon economy and that the required investment would have economic benefits, but it will require large changes in government policy[50].

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[48] Having said that, certain parts of the world have been warm relative to long term norms in the recent past (e.g. the northern polar region around 1940; parts of the world in the medieval warm period) and not all of the world is warming consistently (Antarctica shows little trend warming for example, mostly due to effects associated with the ozone hole and wind). Nevertheless the overall pattern of warming world wide is extremely rapid and is broadly consistent with what could be expected from the anthropogenic and natural forcings.

[49] See chapter 2 and 3

[50] See chapter 3

Further Reading

- IPCC - *Fourth Assessment Report (AR4) – Synthesis Report: http://tinyurl.com/2b6q2m*
- Sir John Houghton – *“Global Warming the Complete Briefing”*
- David Archer – *“Global Warming: Understanding the Forecast”*
- Sir David King – *“The Hot Topic”*
- Mark Lynas – *“Six Degrees”*
- William James Burroughs – *“Climate Change a Multidisciplinary Approach”*
- Robinson and Sellers - *“Contemporary Climatology”*
- Tim Flannery - *“The Weather Makers”*
- James Garvey - *“The Ethics of Climate Change”*
- William James Burroughs - *“Does the Weather Really Matter?”*

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