Lecture 27: Radiative Forcing of Climate Change
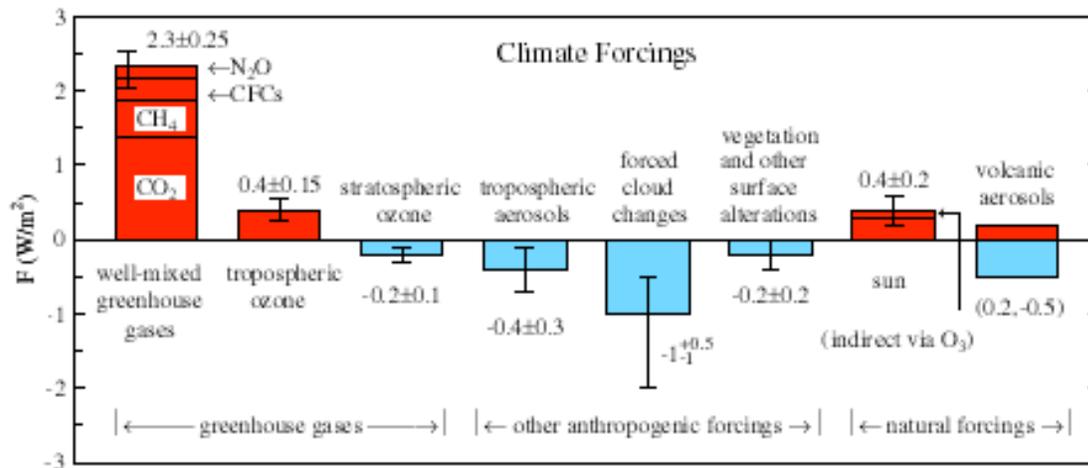
1. Radiative Forcing

In an unperturbed state, the net incoming solar radiation at the top of the atmosphere (Sn) must be balanced by the outgoing longwave radiation (Lo), on an annual basis globally. While this may not be exactly so in any given year, but when a long time series of the annual differences are viewed, Sn must equal Lo.

A true change in either Sn or Lo is called Radiative Forcing.

A positive radiative forcing, that is, when Lo is less than Sn, results in warming of the Earth surface. And, *vice versa.* For instance, increasing the concentration of greenhouse gases in the atmosphere, such as carbon dioxide, decreases the outgoing longwave radiation, and therefore, results in warming of the Earth's surface. On the otherhand, increasing the aerosol loads in the atmosphere, increases the direct effect of reflection of solar radiation by these particulates, and therefore, results in a negative radiative forcing or cooling of the Earth's surface.

Human activities can result in changes of the various components of the climate system, the climatic effects of which can be estimated by investigating the magnitude of radiative forcing. Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial time to the present are shown below.
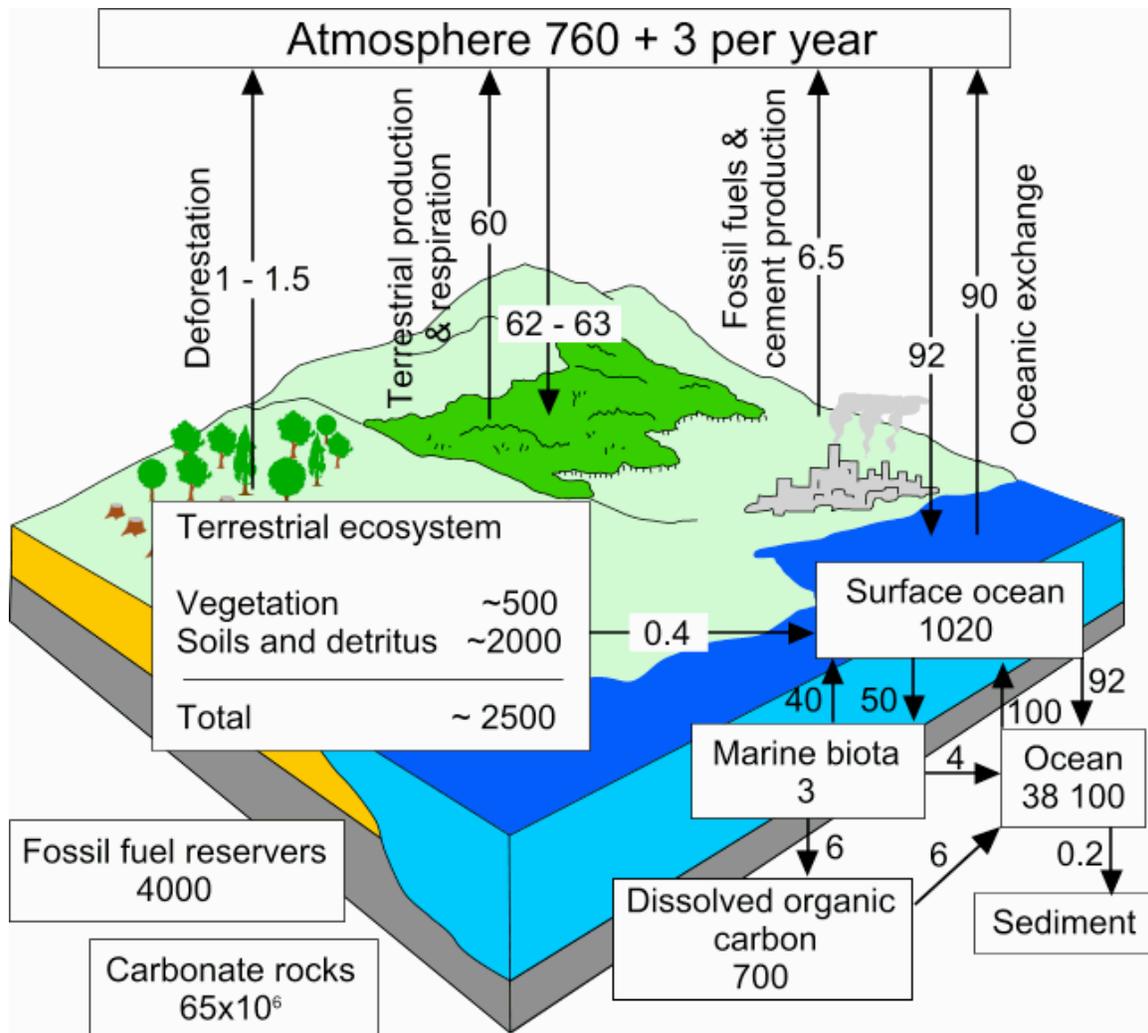

The increase in CO2 concentration from 280 ppmv (preindustrial) to 360 ppmv (1995) resulted in a positive radiative forcing of the climatic system of about 1.5 W/m2. A further 0.5 W/m2 forcing has resulted from increase in methane concentration (700 ppbv preindustrial to 1700 ppbv in 1995). The total radiative forcing due to greenhouse gases is thus estimated to be about 2.5 W/m2. A general rule of thumb is warming of about 0.6 C results from 1 W/m2 forcing of the present climate system.

The negative values for aerosols should not necessarily be seen as an offset against the greenhouse gas forcing because of uncertainties over the applicability of global mean radiative forcing in the case of non-homogeneously distributed species such as aerosols and ozone. It is especially important to note the confidence level associated with tropospheric aersol indirect effects.

2.A. Carbon Budget

The global carbon budget during the 1990s is shown schematically in the figure below. Our understanding of the global carbon cycle has improved considerably in the recent years, particularly in how the carbon from the atmosphere is removed and stored in sinks on land and ocean. However, considerable uncertainity exists regarding the processes which contribute to the sinks on land.

Atmosphere 760 + 3 per year

Deforestation 1 - 1.5
Terrestrial production & respiration 60
62 - 63
Fossil fuels & cement production 6.5
Oceanic exchange 90
92

Terrestrial ecosystem

Vegetation	~500
Soils and detritus	~2000
Total	~ 2500

0.4

Surface ocean 1020

40 50
100 92

Marine biota 3
4
Ocean 38 100

6 6 0.2

Fossil fuel reservers 4000

Dissolved organic carbon 700

Sediment

Carbonate rocks 65x10^6

The main anthropogenic sources of carbon dioxide are the burning of fossil fuels (with additional contributions from *cement production*), and land-use changes. During the 1990s, the average emissions from fossil fuel burning and cement production were 6.5

GtC/yr. A GtC is a Giga Tonne of Carbon or 10^9 (billion) tonnes of carbon or 10^15 (Peta) grams of carbon.

Land-use changes cause both release and uptake of CO_2. On average CO_2 will be released to the atmosphere if the original ecosystem stored more carbon than the modified ecosystem which replaces it. Thus, deforestation acts as a CO_2 source. During the 1990s, tropical deforestation is estimated to have resulted in an average emission to the atmosphere of 1.0 to 1.5 GtC/yr.

Carbon exchanges between vegetation on land and the atmosphere are considerable, at annual scales. Global vegetation fixes about 100-120 GtC/yr through the process of photosynthesis (Gross Primary Production, or GPP). About 40-50% of this carbon is respired by the vegetation (Autotrophic or plant Respiration, AR) , with the result Net Primary Production of global vegetation is about 50 to 60 GtC/yr. Heterotrophs in the soil constribute a similar amout to the atmosphere *(Heterotrophic or soil Respiration, HR)*. The difference between NPP and HR is called Net Ecosystem Exchange or NEE). Carbon from land is also lost through non-respiratory processes, for example, fire, herbivory, harvests, insect damage, river run-off, etc. The resulting balance between carbon gains and losses is called Net Biome Production, NBP. Currently, it is estimated that NBP is about 1-3 GtC/yr, that is, there is a carbon sink on land.

There are also considerable exchanges of CO_2 between the atmosphere and the oceans, of the order of about 90 GtC/yr, with a net sink of about 2 GtC/yr. Carbon in the surface ocean layers is used by the marine biota, and more is exchanged with the intermediate to deep layers in the ocean. The carbon stocks in the ocean are significantly larger than on land. The carbon budget for 1980s and 1990s is shown in the Table below.

	1980s (Gt C/yr)	1990s (Gt C/yr)
Industrial emissions	5.4±0.3	6.3 ±0.4
Land-use change	1.7 (0.6 to 2.5)	Assume 1.6 ±0.8
Ocean-atmosphere flux	-1.9 ±0.5	-1.7 ±0.5
Land-atmosphere flux	-0.2 ±0.7	-1.4 ±0.7
Atmospheric increase	3.3 ±0.1	3.2 ±0.1

2.B. Atmospheric Carbon Dioxide

Accurate and direct measurements of the concentration of CO_2 in the atmosphere began in 1957 at the South Pole and in 1958 at Mauna Loa, Hawaii. The Mauna Loa record is shown below.

Mauna Loa Monthly Mean Carbon Dioxide
NOAA ESRL GMD Carbon Cycle
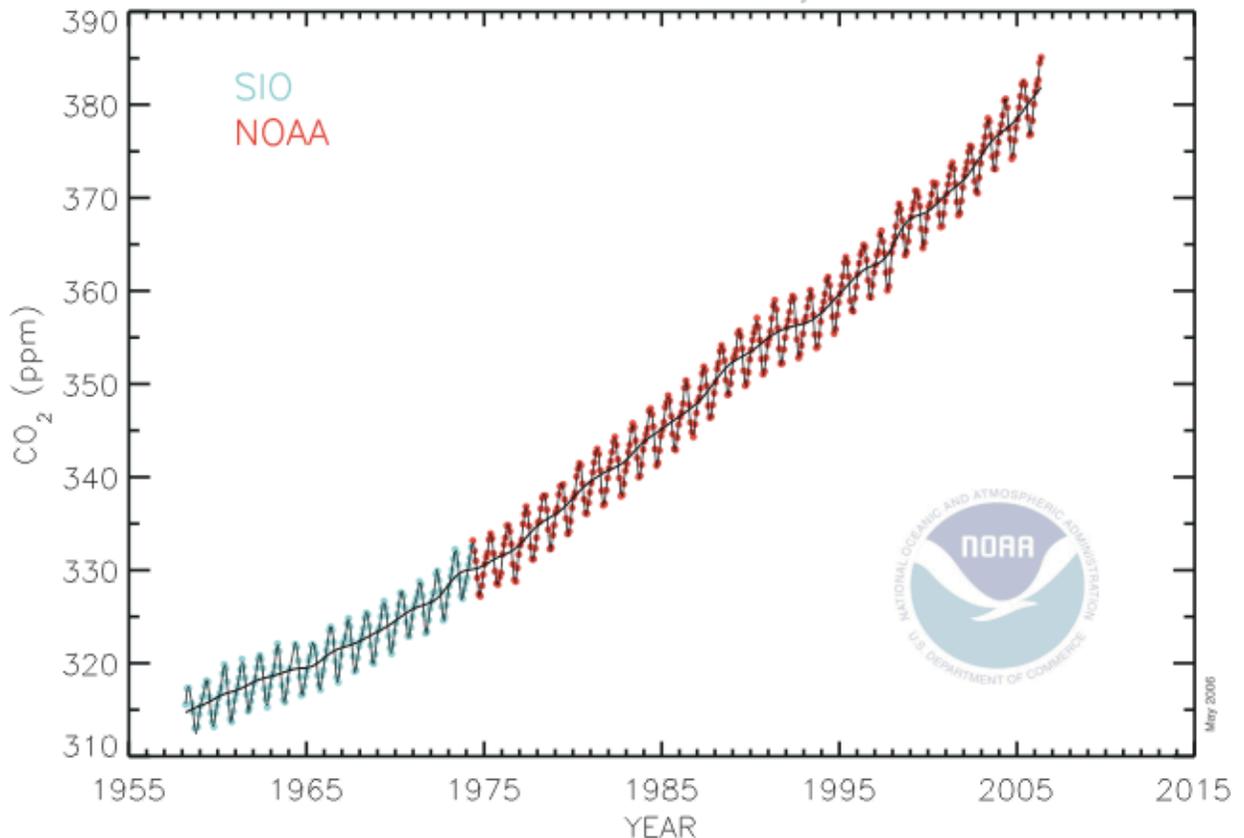
Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, and Dr. Ralph Keeling, SIO GRD, La Jolla, California, (858) 534-7582, rkeeling@ucsd.edu.

In 1958, the concentration of CO2 was about 315 ppmv, and the growth rate was about 0.6 ppmv/yr. This growth rate has generally been increasing since then; it averaged 0.83 ppmv/yr in the 1960s, 1.28 ppmv/yr during the 1970s, amd 1.53 ppmv/yr during the 1980s. The concentration in the spring of 2005 was about 380 ppmv. Data from Mauna Loa are close to, but are not precisely the global mean value. The Mauna Loa record is due to Prof. Keeling of the Scripps Institution of Oceanography.

The annual cycle in the Mauna Loa record is due to the seasonality of vegetation. In early spring, the concentration of CO2 is at its maximum, and as the plants greenup, the concentration drops, reaching a minimum value towards the end of the summer, and when it starts to build up again. This swing in the amplitude is most pronounced in the records from the northern high latitudes, where it can be as large as 15 ppmv.

The atmospheric CO2 record prior to 1957 comes mainly from air bubbles in ice cores, which is reasonably accurate. This record extends back almost a 160,000 years. Over the last 1000 years, CO2 concentration in the atmosphere has fluctuated at about +/- 10 ppmv

around 280 ppmv. The 20th century increase in CO2 concentration is unparalleled in the past 160,000 years.
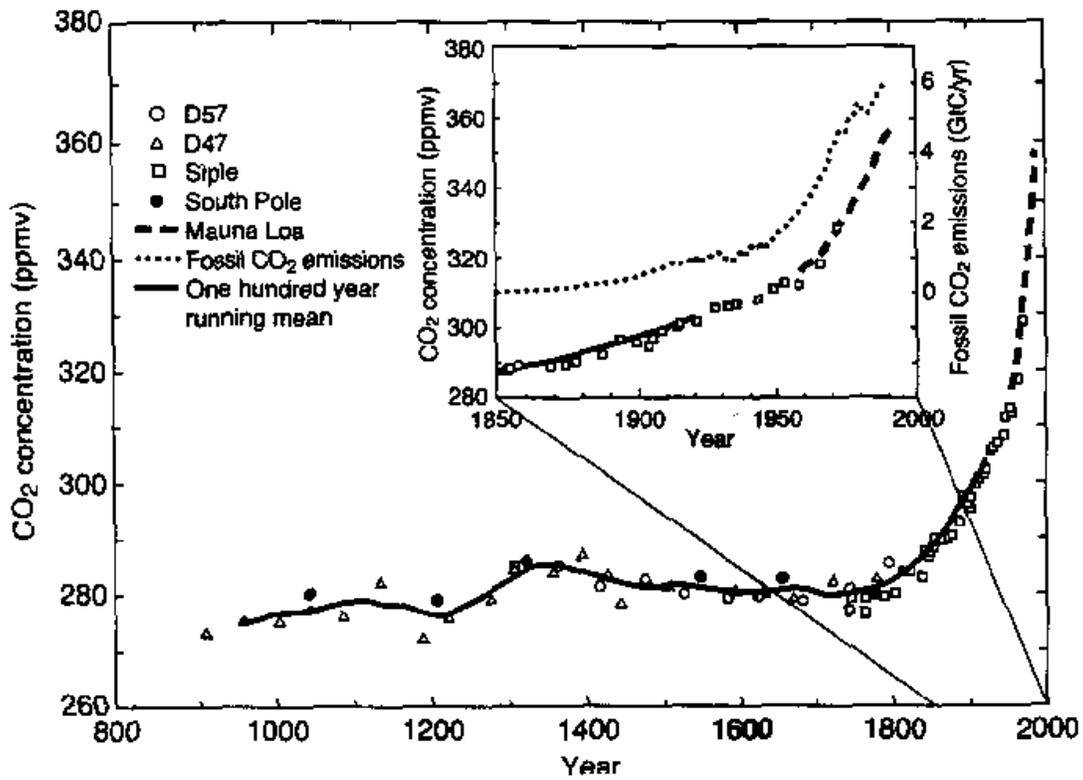

Measurements of the Greenhouse Gas Carbon Dioxide (CO₂) Have Been Taken from Several Ice Cores. Data from the Vostok and Siple Cores Show That CO₂ Concentrations Are Currently at Their Highest Level in the 160,000 Year Record.
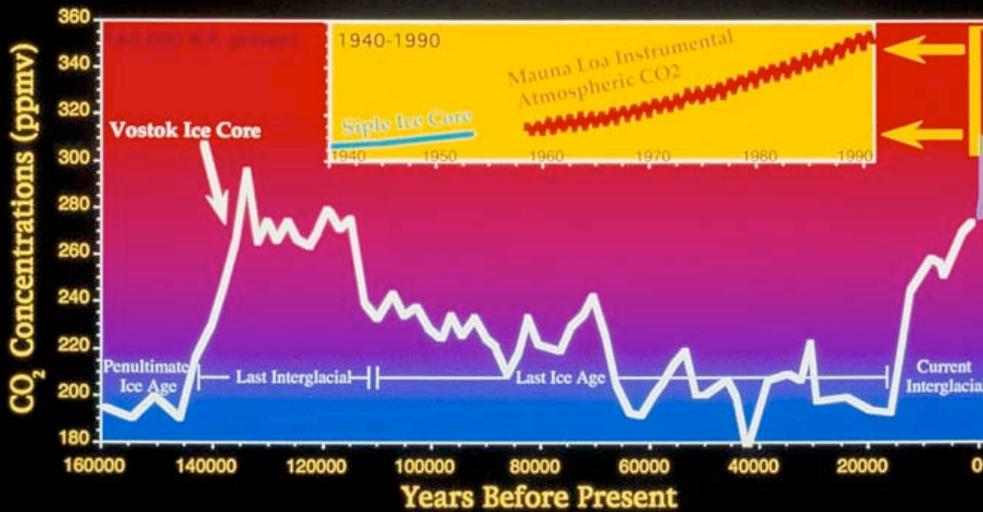
Sources: Vostok: Barnola et al. (1987); Siple: Friedli et al. (1986); Mauna Loa: Keeling and Whorf (1991).

There are at least three arguments to be made for the case that the observed increase in atmospheric CO2 concentration is due to emissions related to human activity.

- The rise in atmospheric CO2 concentration closely follows the increase in emissions related to fossil fuel burning and cement production.

- The inter-hemispheric gradient in atmospheric CO2 concentration is growing in parallel with CO2 emissions. That is, there is more land mass in the Northern hemisphere, and therefore more human activity, and thus, higher emissions, which is reflected in the CO_2 growth in the Northern hemisphere (compared to the SH).
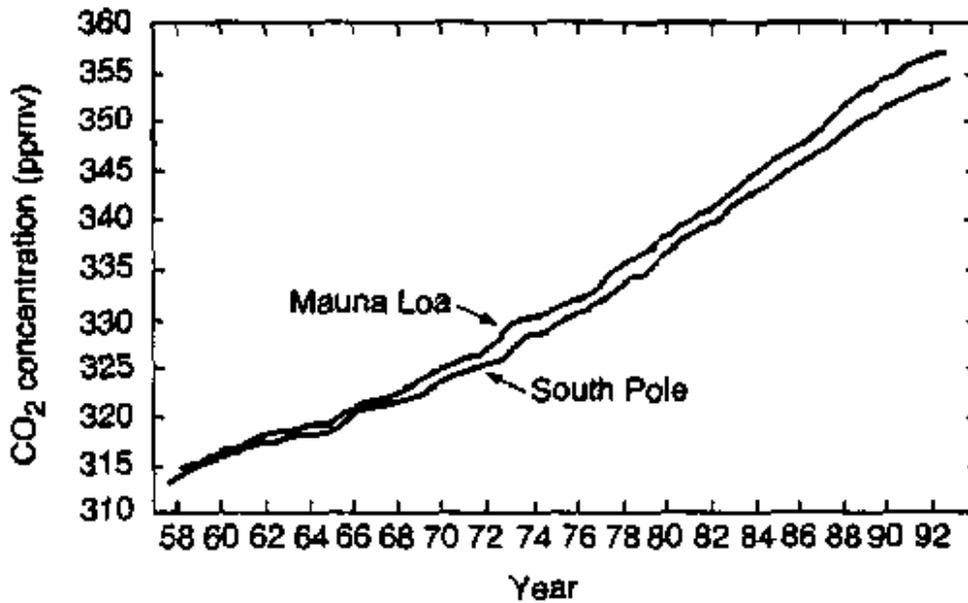

- Fossil fuels and biospheric carbon are low in Carbon 13 (an isotope). The ratio of carbon 13 to carbon 12 in the atmosphere has been decreasing.

3. Methane
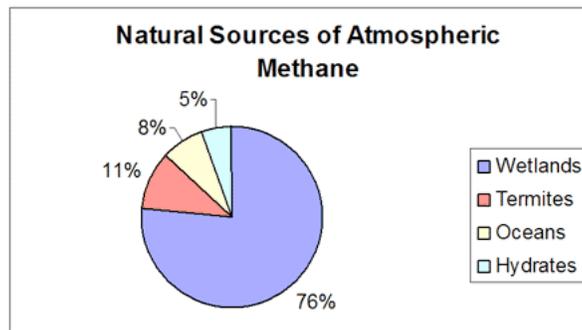
Methane (CH4) is another naturally occurring greenhouse gas whose concentration in the atmosphere has been increasing as a result of human activities (rice paddies, animal husbandry, landfills, biomass burning, and fossil fuel production and use). Ice core measurements of methane concentration indicate that its concentration has increased from a preindustrial level of about 750 ppbv to over 1750 ppbv in 2003.

Note that although methane concentration is in ppbv, compared to carbon dioxide, it is a highly effective radiative gas. The increase in methane since preindustrial times is estimated to have resulted in a radiative forcing of about 0.5 W/m2, which is quite significant when compared to the increase in carbon dioxide concentration during the same time period and its radiative forcing (1.5 Watts/m^2).
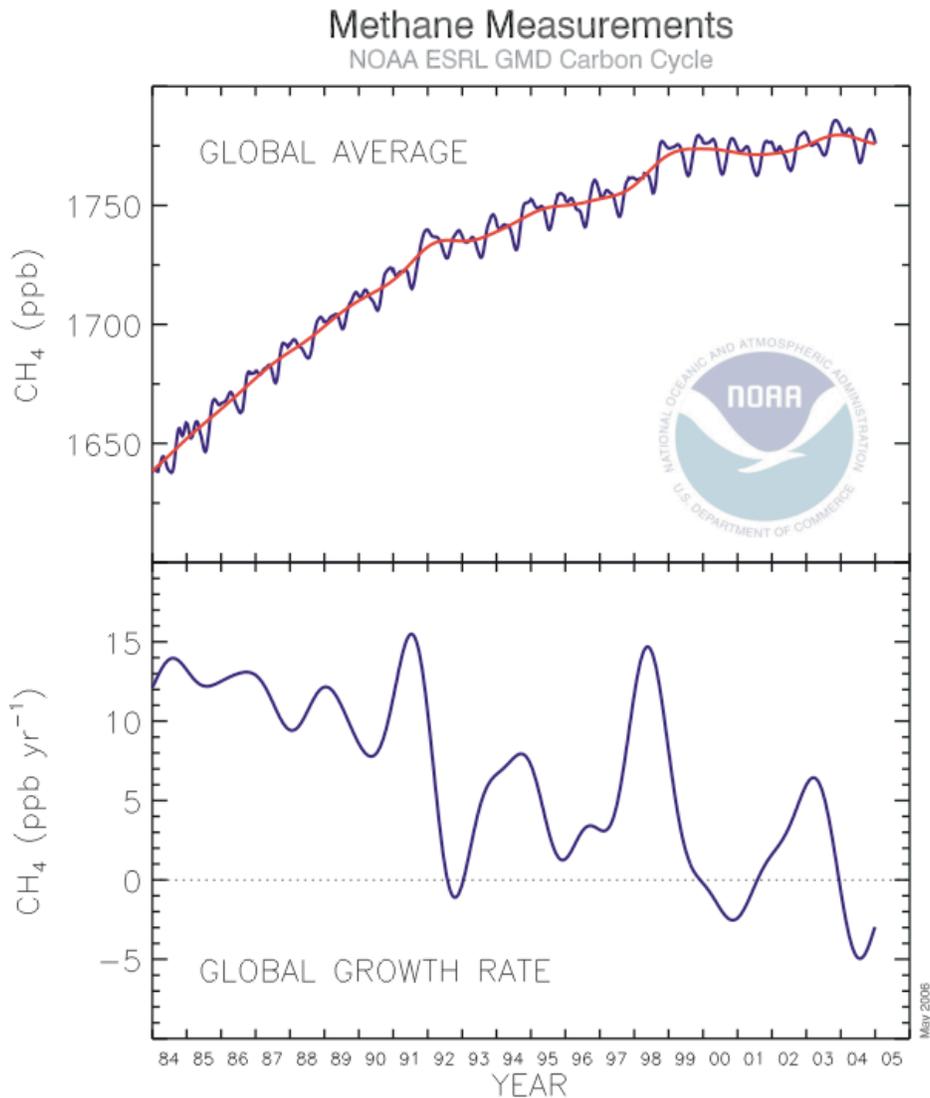

Top: Global average atmospheric methane mixing ratios (blue line) determined using measurements from the GMD cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for methane. Contact: Dr. Ed Dlugokencky, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6228 (ed.dlugokencky@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

5. Aerosols

Aerosols are suspensions of particles in the atmosphere, with diameters in the range 10^{-3} to 10^{-6} meters. Tropospheric aerosols are formed by -

- dispersal of material from the surface, for example dust,
- direct emission of material into the atmosphere, for example, smoke,
- chemical reactions in the atmosphere which convert gases, such as sulphur dioxide, into particles.

The release of sulphur dioxide from fossil fuel combustion and biomass burning, are the main anthropogenic sources of aerosols. Averaged over the globe, aerosols made by human activities currently account for about 10 percent of the total amount of aerosols in our atmosphere. Most of that 10 percent is concentrated in the Northern Hemisphere, especially downwind of industrial sites, slash-and-burn agricultural regions, and overgrazed grasslands.
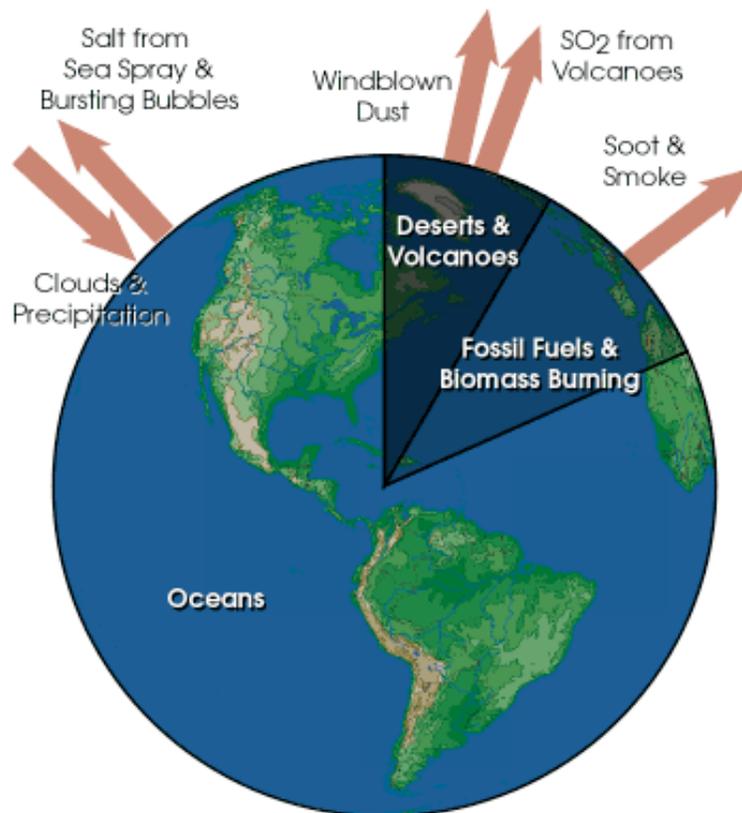
The addition of tropospheric aerosols from anthropogenic sources can influence the radiative balance in two major ways -

- Direct Effect: Aerosols tend to cause cooling of the Earth's surface immediately below them. Because most aerosols reflect sunlight back into space, they have a "direct" cooling effect by reducing the amount of solar radiation that reaches the surface. The magnitude of this cooling effect depends on the size and composition of the aerosol particles, as well as the reflective properties of the underlying surface. It is thought that aerosol cooling may partially offset expected global warming that is attributed to increases in the amount of carbon dioxide from human activity.

- Indirect Effect: Aerosols are also believed to have an "indirect" effect on climate by changing properties of clouds. Indeed, if there were no aerosols in the atmosphere, there would be no clouds. It is very difficult to form clouds without small aerosol particles acting as "seeds" to start the formation of cloud droplets. As aerosol concentration increases within a cloud, the water in the cloud gets spread over many more particles, each of which is correspondingly smaller. Smaller particles fall more slowly in the atmosphere and decrease the amount of rainfall. In this way, changing aerosols in the atmosphere can change the frequency of cloud occurence, cloud thickness, and rainfall amounts. If there are more aerosols, scientists expect more cloud drops to form. Since the total amount of condensed water in the cloud is not expected to change much, the average drop must become smaller. This has two consequences -- clouds with smaller drops reflect more sunlight, and such clouds last longer, because it takes more time for small drops to coalesce into drops that are large enough to fall to the ground. Both effects increase the amount of sunlight that is reflected to space without reaching the surface.

There are many uncertainities associated with how aerosols influence the climate. Aerosols are highly variable spatially, both in their concentration and chemical composition, and direct observations of their amount and kind are begining to emerge just now. Nevertheless, some attempts have been to estimate the globally averaged radiative forcing due to aerosols from anthropogenic sources. The direct radiative forcing due to increases in sulphate aerosol since 1850, averaged globally, is estimated to lie between -0.25 to -0.9 W/m2. And, the direct effect of aerosol from biomass burning is estimated to be in the range of -0.05 to -0.6 W/m^2.