The current rate of CO_2 emission due to fossil fuel consumption is

5.5 Gt C/yr — average per capita rate ~ 1 ton/person-yr

This includes a small fraction due to cement production:

limestone + heat → lime or cement + CO_2 (emitted to atmosphere)

$CaCO_3 \longrightarrow CaO + CO_2$

$CaO + H_2O \rightarrow Ca(OH)_2$ (concrete)

The observed secular rate of increase of atmospheric CO_2 is

1.5 ppm/yr or $\frac{1.5}{360} = 0.4\%$ /yr

The pre-industrial level (constant for ~ 1000 years):

280 ppm CO_2 pre-industrial

Current level: 360 ppm (760 GtC in atmosphere)

observed rate of increase $.0042 \times 760 = 3.2$ GtC/yr

This discrepancy is known as the missing carbon problem.

Current understanding of carbon budget:

fossil fuel & cement	5.5 GtC/yr
tropical deforestation	1.6 GtC/yr
	7.1 GtC/yr total

where is it going?

atmosphere	3.2 GtC/yr
ocean uptake	2.0 Gt/yr
N forest regrowth	0.5 GtC/yr
	5.7 GtC/yr

"Missing" carbon 1.4 ± 1.5 GtC/yr — may be no problem at all

Suggestions abound

(1) CO_2 fertilization — would need $\frac{1.4}{65} = 2\%$ increase/yr in NPP

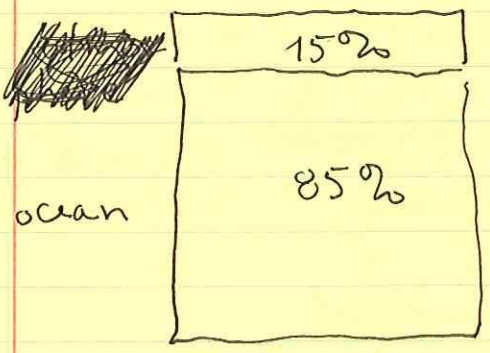
(2) nitrogen fertilization — increased phytoplankton production due to fertilizer runoff

The oceans are able to take up much more carbon than the atmosphere (stored as carbonate & bicarbonate ions)

$$CO_2 + H_2O \longleftrightarrow HCO_3^- + H^+ \longleftrightarrow CO_3^{2-} + 2H^+$$

0.5% of C 88.9% of C 10.0% of C

The ultimate fate of CO_2 released by fossil fuel burning:



The time scale for oceanic uptake is ~ 1000 years — very long by human standards

The increase of atmospheric CO_2 from 280 ppm to 360 ppm has increased the "thickness" of the greenhouse "glass"

How much? Known very well — forcing increased by

$$1.6 \frac{W}{m^2} = \frac{1.6}{340 \times 1.14} = 0.5\%$$

$$\text{forcing } \frac{\Omega}{4} \times \frac{114 \text{ units}}{100 \text{ units}} \Rightarrow 288°K$$

Other human activities have also affected the greenhouse forcing:

methane
halocarbons — CFCs
} other absorbers

aerosols — increase albedo by $\sim 0.3\%$
$\Rightarrow$ forcing decreased by

$$-0.03 \times 340 \times 1.14 = -1 \text{ W/m}^2$$

Total anthropogenic increase in radiative forcing:

2 W/m² increased forcing

Expected rise in temperature

$$\sigma T^4 = u_0 = 340 \times 1.14 \text{ W/m}^2$$

$$\sigma (T + \Delta T)^4 = u_0 + \delta u_0$$

For $\Delta T \ll T$: $(T + \Delta T)^4 = T^4 + 4T^3 \Delta T + \cdots$

$$\sigma T^4 + 4\sigma T^4 \frac{\Delta T}{T} = u_0 + \delta u_0$$

$$\frac{\Delta T}{T} = \frac{1}{4}\left(\frac{\delta u_0}{u_0}\right) \qquad \Delta T \approx 0.4^\circ C$$

This purely radiative equilibrium calculation ignores feedbacks.

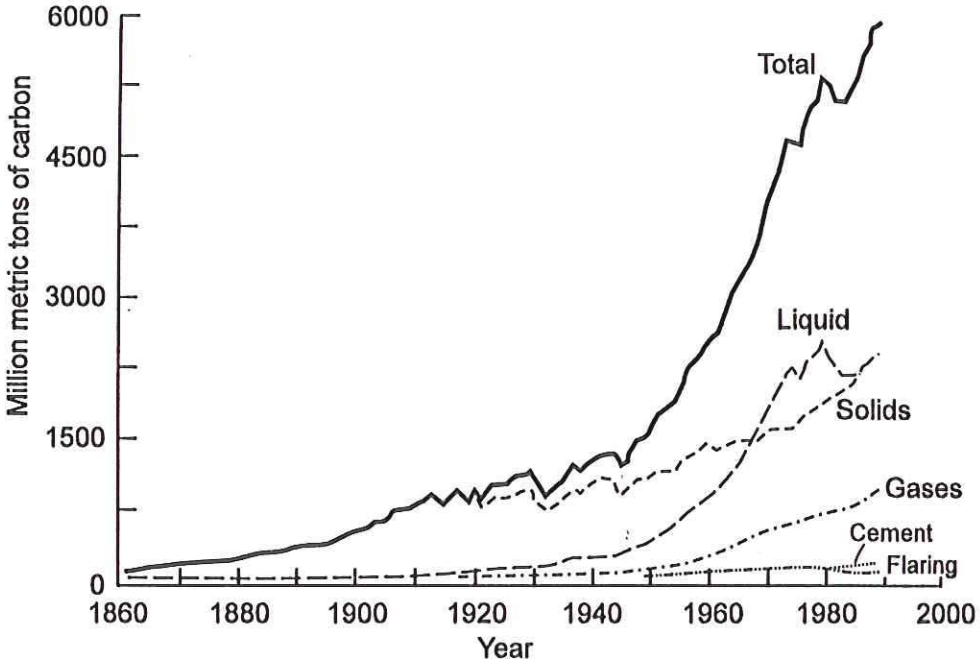
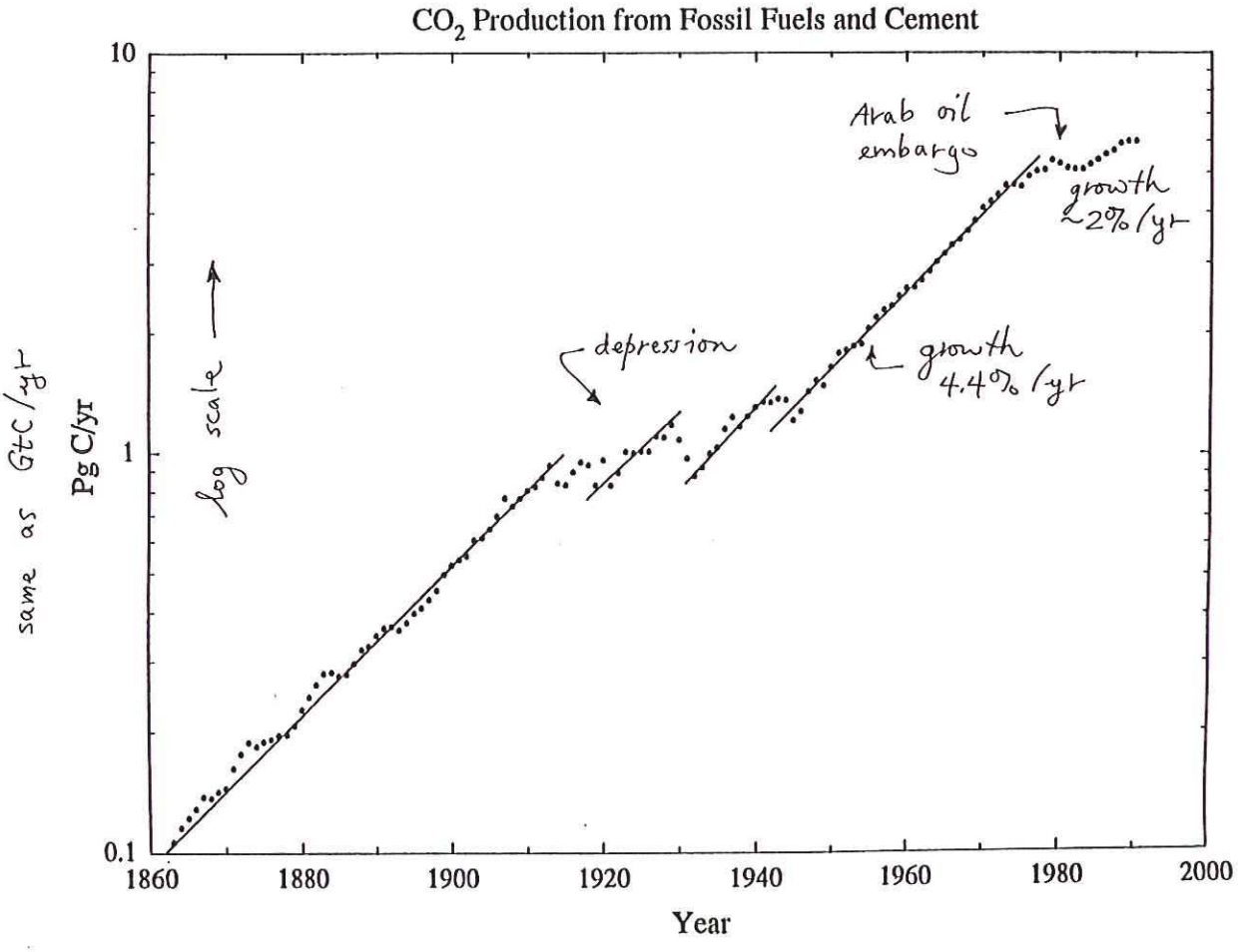


Figure 11.18. Global CO_2 emissions from fossil fuel burning and cement manufacture, 1860–1989. (From *Trends '91: A Compendium of Data on Global Change*)



The anthropogenic contribution

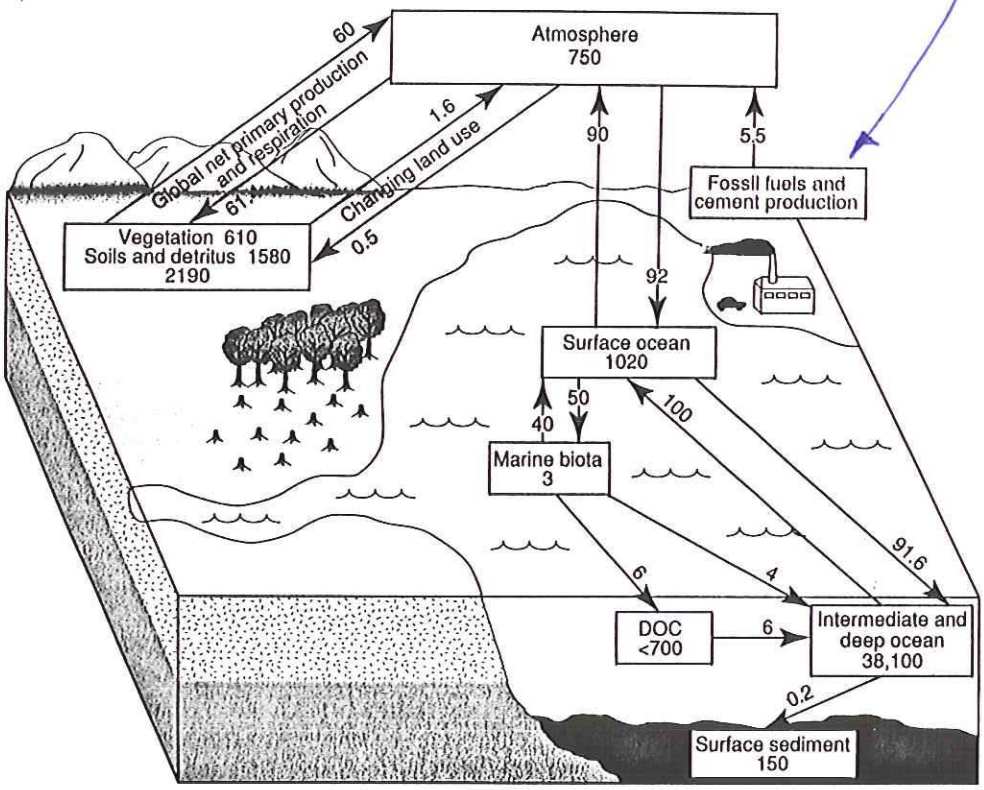
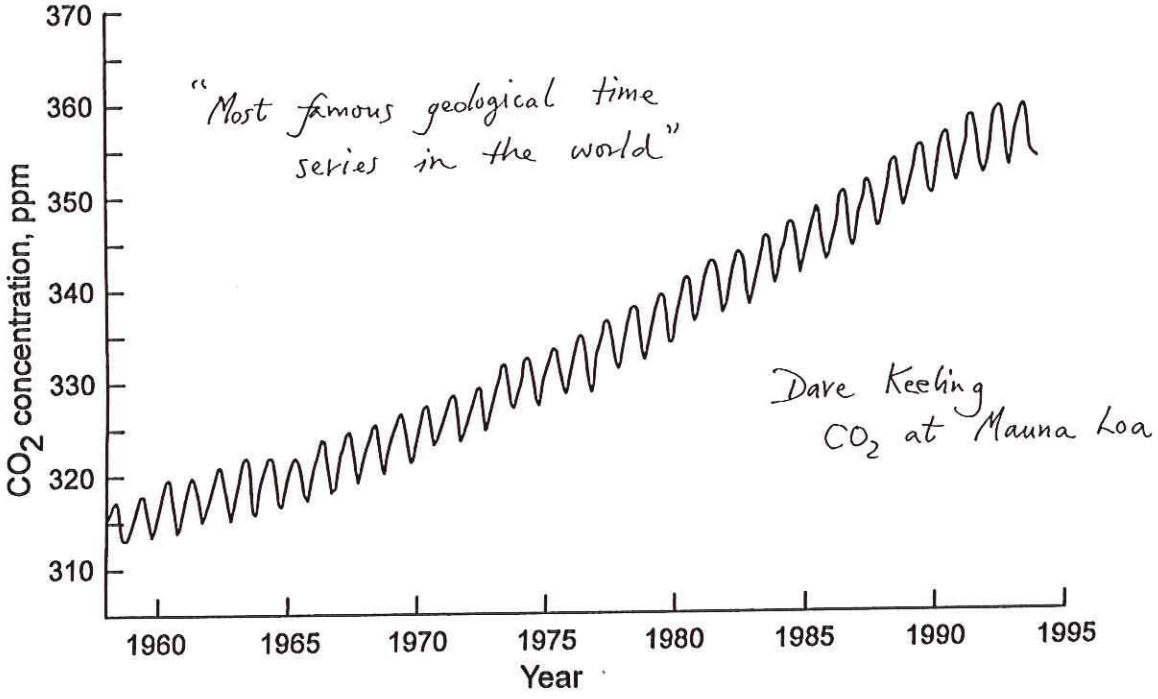


Figure 4: The global carbon cycle. The numbers in boxes indicate the size in GtC of each reservoir. On each arrow is indicated the magnitude of the flux in GtC/yr (DOC = dissolved organic carbon).



Secular increase of atmospheric CO_2 is global

1.5 ppm/yr or 0.42 %/yr

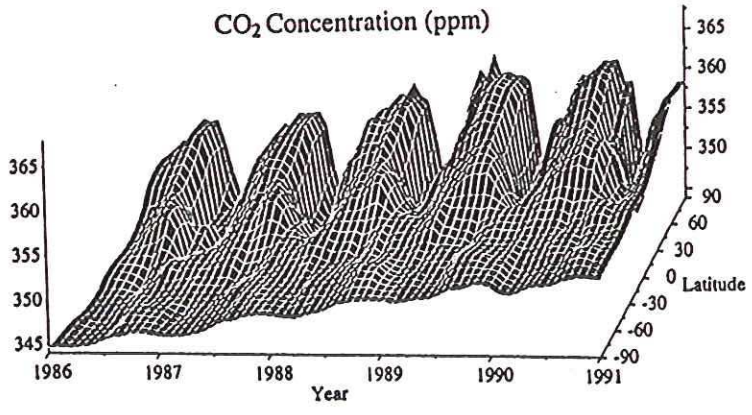
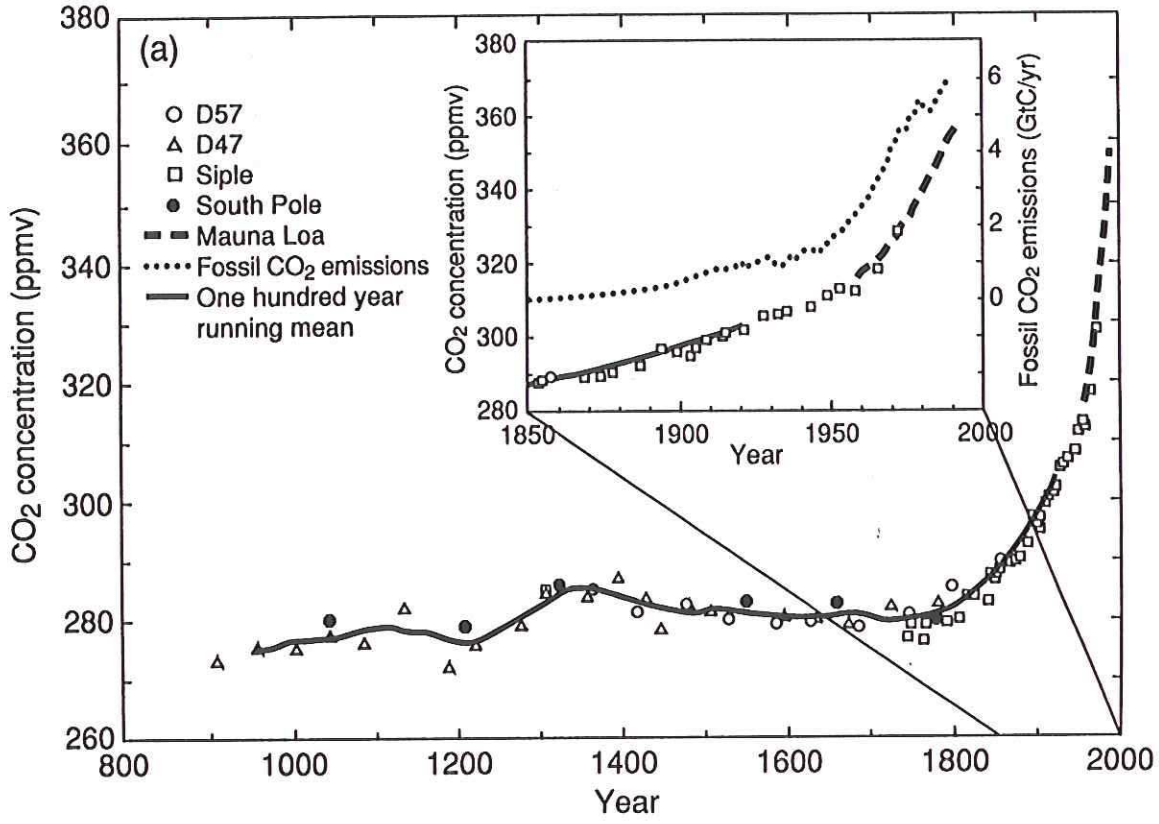
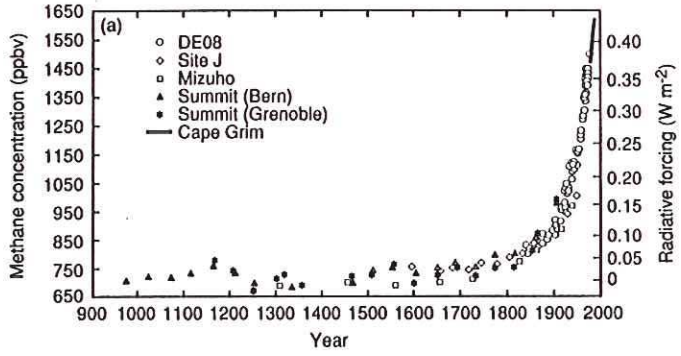


Fig. 9. Smoothed atmospheric CO_2 data as measured by the National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory's Flask Sampling Program (Conway et al. 1991).





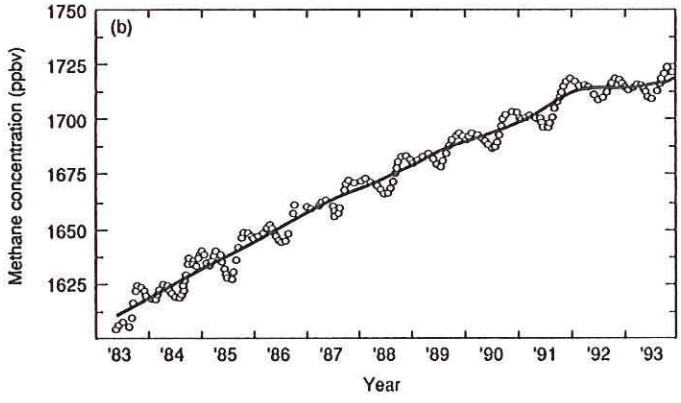
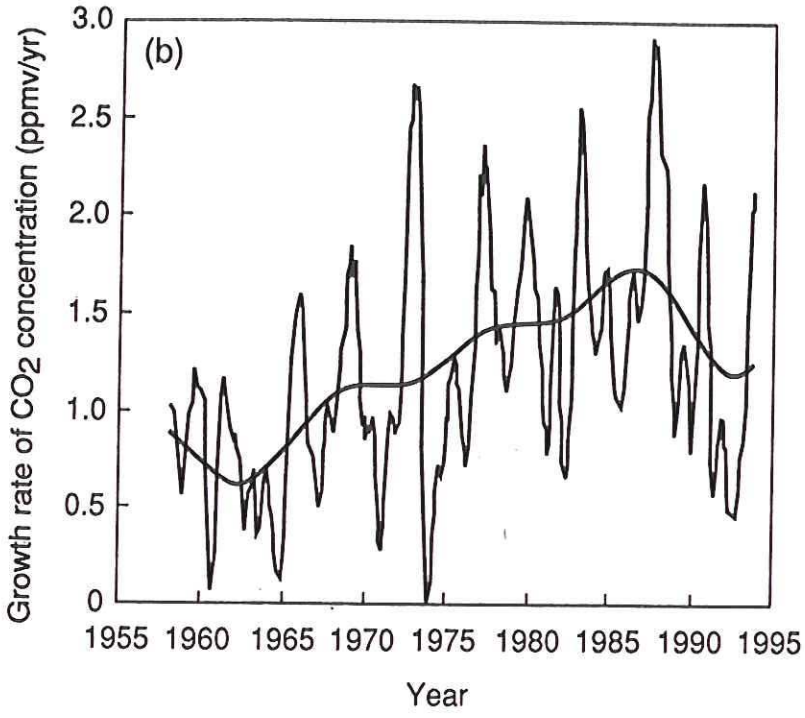


Figure 9: (a) CH_4 concentration derived from Antarctic ice cores over the past 1000 years. Direct observations of CH_4 concentration from Cape Grim, Tasmania, are included to demonstrate the smooth transition from ice core to atmospheric measurements. The radiative forcing resulting from increases in CH_4 relative to the pre-industrial period are indicated on the right-hand axis. The effect of overlap with N_2O is accounted for according to IPCC (1990). (b) Globally averaged CH_4 concentration for 1983 to 1993 showing the decline in growth rate during 1992 and 1993.



Atmospheric CO_2 growth rate 1.5 ppm/yr
or 0.42 %/yr

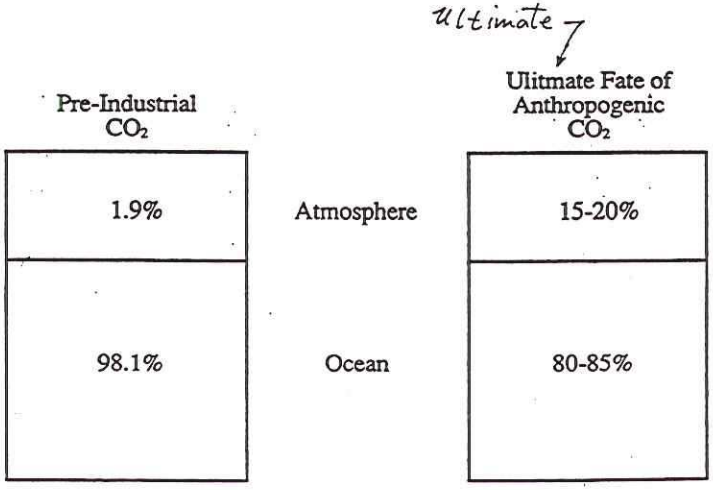
(0.0042)(760 GtC in atmosphere) = 3.2 GtC/yr

Anthropogenic emission rate is 5.5 GtC/yr

This is the "missing carbon" problem

***Table 1:** Annual average anthropogenic carbon budget for 1980 to 1989. CO_2 sources, sinks and storage in the atmosphere are expressed in GtC/yr.*

CO_2 sources		
(1) Emissions from fossil fuel and cement production	5.5 ± 0.5	
(2) Net emissions from changes in tropical land-use ← deforestation	1.6 ± 1.0	
(3) Total anthropogenic emissions = (1)+(2)	7.1 ± 1.1	
Partitioning amongst reservoirs		
(4) Storage in the atmosphere	3.2 ± 0.2	
(5) Ocean uptake	2.0 ± 0.8	
(6) Uptake by Northern Hemisphere forest regrowth	0.5 ± 0.5	
(7) Additional terrestrial sinks (CO_2 fertilisation, nitrogen fertilisation, climatic effects) = [(1)+(2)]-[(4)+(5)+(6)]	1.4 ± 1.5 ←	the "missing carbon"



Time Scale of Oceanic Uptake of Anthropogenic CO_2

% of CO_2 Molecules	Mean Life in Atmosphere (years)
6	1
23	10
30	61
25	359
16	≥ Thousands of years

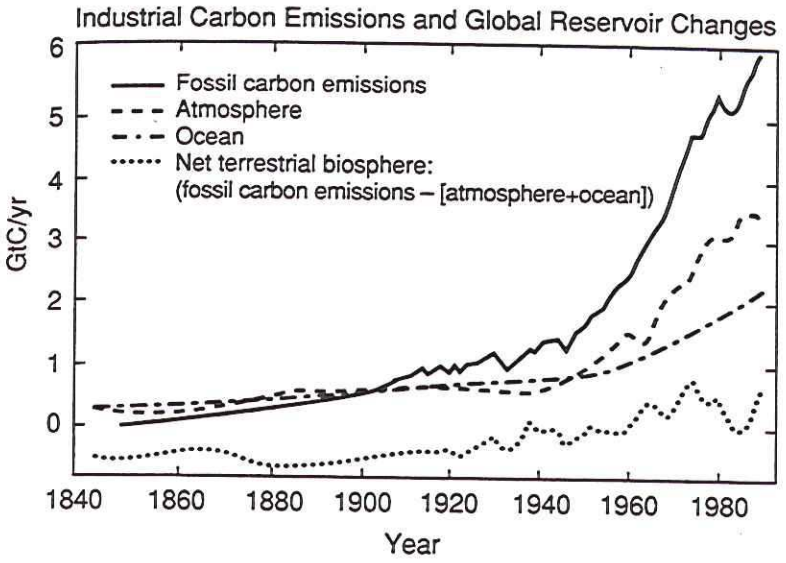


Figure 1.7: Fossil carbon emissions (based on statistics of fossil fuel and cement production), and representative calculations of global reservoir changes: atmosphere (deduced from direct observations and ice core measurements), ocean (calculated with the GFDL ocean carbon model), and net terrestrial biosphere (calculated as remaining imbalance). The calculation implies that the terrestrial biosphere represented a net source to the atmosphere prior to 1940 (negative values) and a net sink since about 1960.

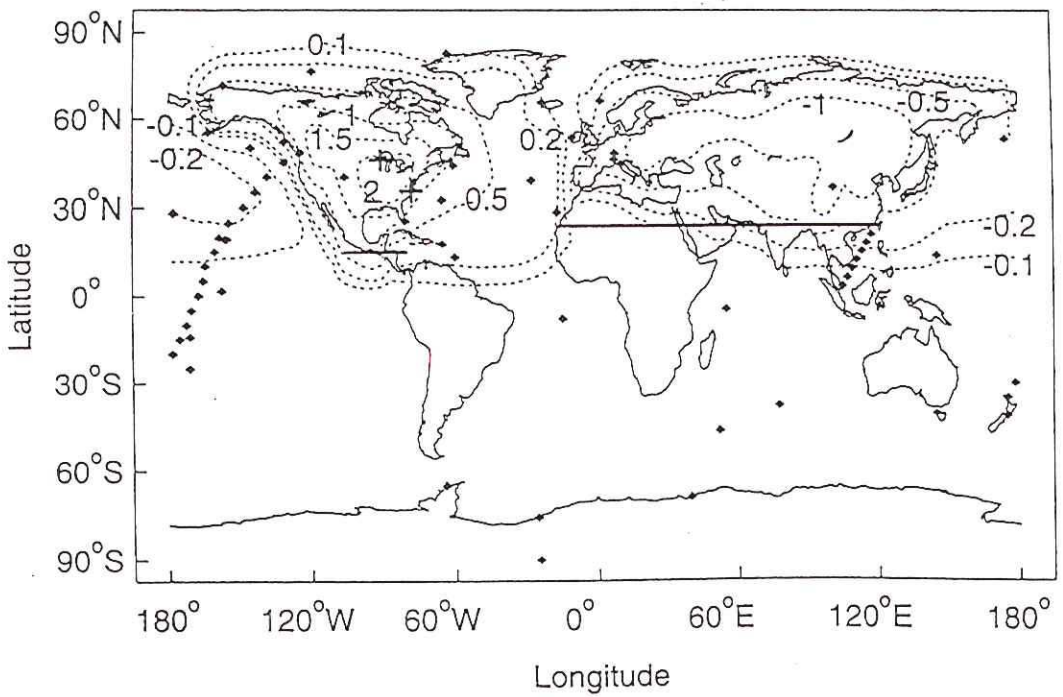


Fig. 1. A map of the atmospheric CO_2 sampling network. Sites are shown as solid diamonds. (The Globalview labels for the Northern Hemisphere stations are given in the legend of Fig. 3). The tall tower sites are shown as crosses. The thick horizontal lines divide the land surfaces into three regions where terrestrial carbon uptake has been estimated: North America, Eurasia–North Africa, and Tropics and Southern Hemisphere. The dotted contour lines show the difference between predicted surface CO_2 concentrations (ppm) with estimated terrestrial uptake and with North American terrestrial uptake set to zero (model results are shown for GCTM with the T97 sea-air fluxes).

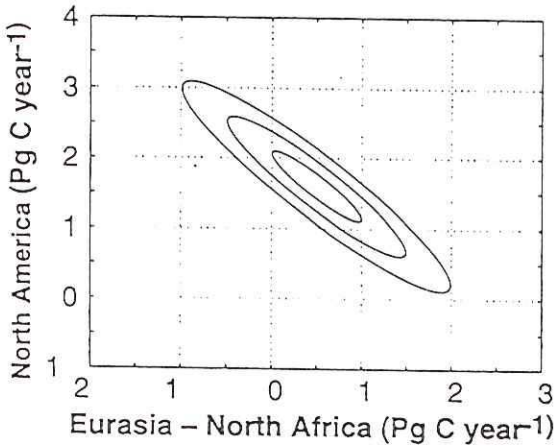


Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

Table 2. Estimated terrestrial carbon uptake for 1988 to 1992. Positive terrestrial carbon uptake is a flux out of the atmosphere. GCTM and SKYHI are the two atmospheric GCM models and T97 and OBM are the two air-sea flux estimates used in the inversions (see text).

Source region	Terrestrial uptake (Pg C year^{-1})				SD of the estimate* (Pg C year^{-1})	Mean and summary SE† (Pg C year^{-1})	Forest area (10^9 ha)
	GCTM		SKYHI				
	T97	OBM	T97	OBM			
Three-region inversion							
North America	1.6	1.7	1.7	1.7	±0.5	1.7 ± 0.5	0.8
Eurasia and North Africa	0.5	0.5	−0.4	−0.2	±0.5	0.1 ± 0.7	1.2
Tropics and Southern Hemisphere	0.1	−1.1	0.9	−0.5	±0.1	−0.2 ± 0.9	2.1
Total	2.2	1.1	2.2	1.1	–	–	–
Four-region inversion							
North America							
Boreal	0.4	−0.1	0.5	0.1	±0.3	0.2 ± 0.4	0.4
Temperate	1.2	1.7	1.2	1.3	±0.4	1.4 ± 0.5	0.4
Eurasia and North Africa	0.6	0.7	−0.4	0.0	±0.5	0.2 ± 0.7	1.2
Tropics and Southern Hemisphere	0.0	−1.3	0.9	−0.4	±0.1	−0.2 ± 0.9	2.1
Total	2.2	1.1	2.2	1.1	–	–	–

*The SD of the estimate was found by assuming that the Gaussian variance equals χ^2/q (q = 63) (10), and that data errors from different stations are independent. SDs of estimates obtained with T97 include the sampling uncertainty for oceanic CO_2 exchange (15), but those obtained with OBM include no oceanic uncertainty. However, the contribution of T97 error to the total uncertainty is small. †This is the mean of the estimates from the four combinations of atmospheric and oceanic models. The SE is $\sqrt{\sigma^2+V^2}$, where σ is the SD from the adjacent column and V is the SD of the four estimates in the first four columns.

Table 1. Effect of various anthropogenic gases on the radiative balance of air. Middle column: efficiency of radiative forcing, expressed as a function of absorption per added molecule, with $CO_2 = 1$. Right-hand column: changes in radiative forcing between 1765 and 1990 due to increasing concentrations (Shine et al. 1990). The methane forcing change also includes the indirect effect due to formation of water vapor in the stratosphere

Gas	Normalized forcing per added molecule	Forcing change 1765–1990 ($W\ m^{-2}$)
CO_2	1	1.50
CH_4	21	0.56
N_2O	206	0.10
CFC-11	12 400	0.062
CFC-12	15 800	0.14
Other CFCs		0.085
		2.45

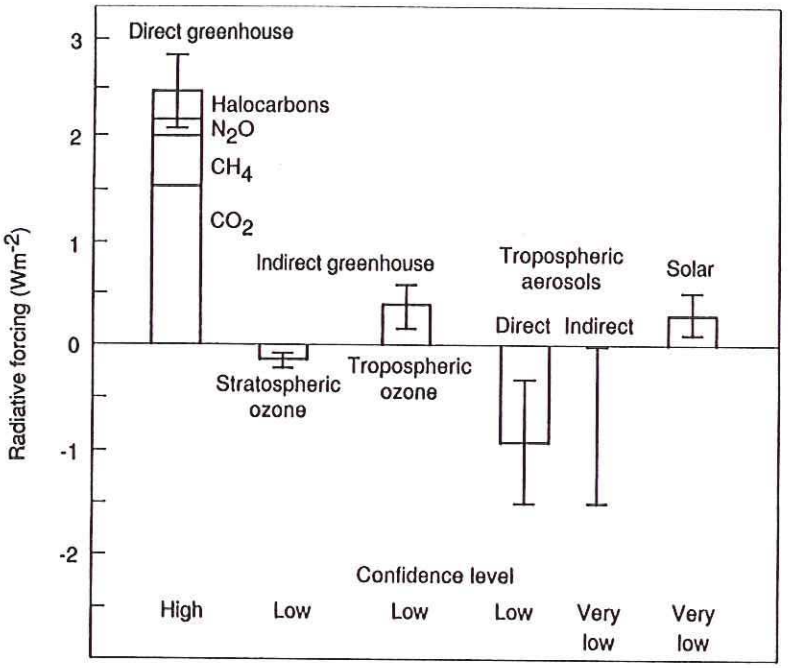


Figure 3: Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial times to the present day and changes in solar variability from 1850 to the present day. The height of the bar indicates a mid-range estimate of the forcing whilst the lines show the possible range of values. An indication of relative confidence in the estimates is given below each bar. The contributions of individual greenhouse gases are indicated on the first bar for direct greenhouse gas forcing. The major indirect effects are a depletion of stratospheric ozone (caused by the CFCs and other halocarbons) and an increase in the concentration of tropospheric ozone. The negative values for aerosols should not necessarily be regarded as an offset against the greenhouse gas forcing because of doubts over the applicability of global mean radiative forcing in the case of non-homogeneously distributed species such as aerosols and ozone (see Section 1 and Section 7).

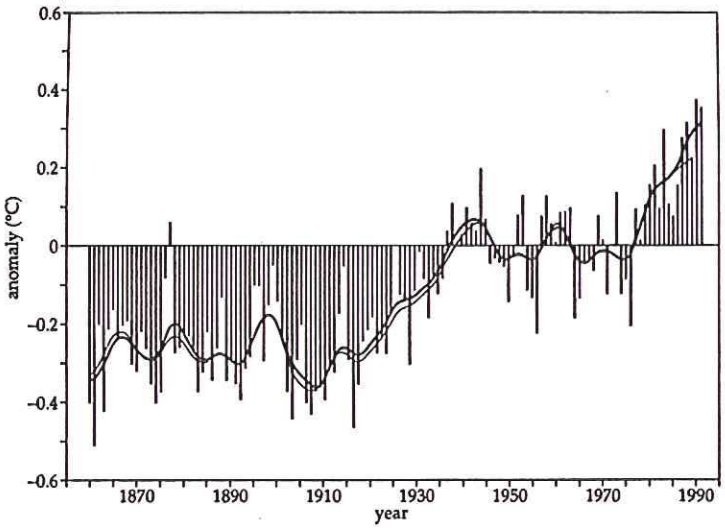
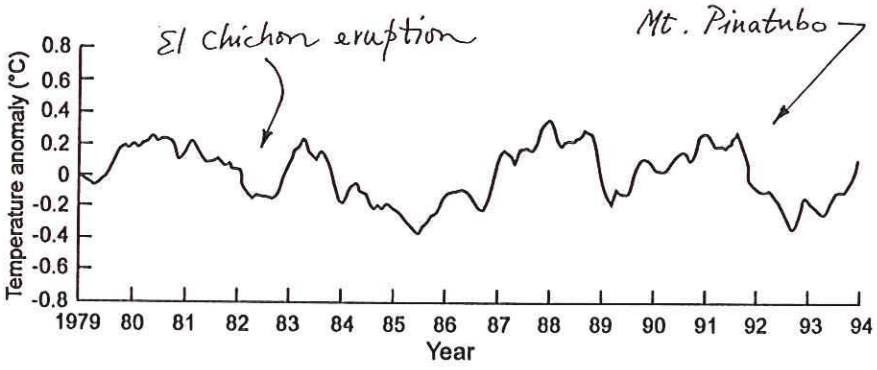


Figure 1.9 Combined land, air and sea surface temperature anomalies between 1861 and 1991, relative to the average temperature 1951–1980. (From IPCC 1992.)

Figure 11.22. Mean global tropospheric temperature anomalies from satellite data (85°S–85°N) from 1979 to 1993. (Data from R. W. Spencer and J. R. Christy; Halpert et al. 1994; see also Kerr 1995)



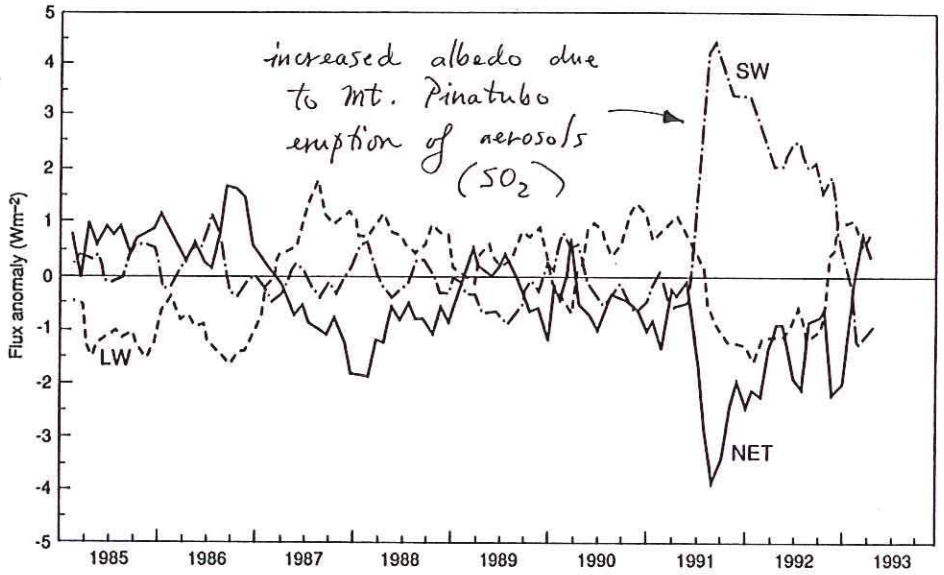


Figure 4.6: Time series of smoothed wide field of view Earth Radiation Budget Experiment long-wave (LW), short-wave (SW) and net (LW-SW) irradiance anomalies (in Wm^{-2}) between 40°N and 40°S relative to the 5 year (1985-1989) monthly mean (after Minnis *et al.*, 1993, updated by Minnis, 1994). The deviation starting in mid-1991 is mainly due to the Mt. Pinatubo eruption – the net anomaly in August (about -4 Wm^{-2}) is almost three times higher than the standard deviation computed between 1985 and 1989.