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

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

This includes a small fraction due to cement production:

$$\overset{\text{limestone}}{CaCO_3} \xrightarrow{\text{heat}} \overset{\text{lime or cement}}{CaO} + \overset{\text{emitted to atmosphere}}{CO_2}$$

$$CaO + H_2O \rightarrow \underset{\text{concrete}}{Ca(OH)_2}$$

The observed secular rate of increase of atmospheric CO_2 is

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

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

$$\frac{1.4}{65} = 2\% \text{ increase / yr in NPP}$$

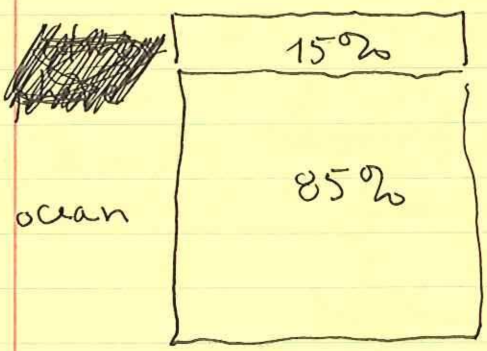
(2) nitrogen fertilization — increased phytoplankton production due to fertilizer runoff

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 <u>ultimate</u> 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

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

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

Other human activities have also affected the greenhouse forcing:

$$\left.\begin{array}{l}\text{methane}\\ \text{halocarbons — CFC's}\end{array}\right\rangle \text{ other absorbers}$$

aerosols — increase albedo by ~ 0.3%
⇒ forcing decreased by

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

Total anthropogenic increase in radiative forcing: $\boxed{2 \ \mathrm{W/m^2} \text{ increased forcing}}$

Expected rise in temperature

$$\sigma T^4 = \varpi_0 = 340 \times 1.14 \ \mathrm{W/m^2}$$

$$\sigma (T + \Delta T)^4 = \varpi_0 + \delta\varpi_0$$

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

$$\cancel{\sigma T^4} + 4\sigma T^4 \frac{\Delta T}{T} = \cancel{\varpi_0} + \delta\varpi_0$$

$$\boxed{\frac{\Delta T}{T} = \frac{1}{4}\left(\frac{\delta\varpi_0}{\varpi_0}\right) \qquad \Delta T \approx 0.4\,^\circ\mathrm{C}}$$

This purely radiative equilibrium calculation ignores feedbacks.

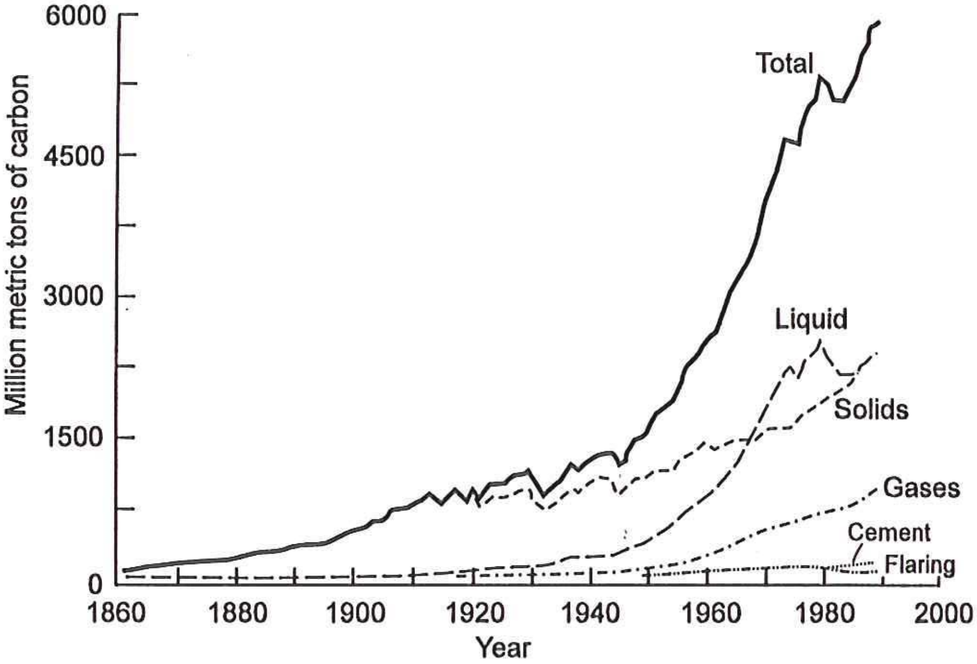
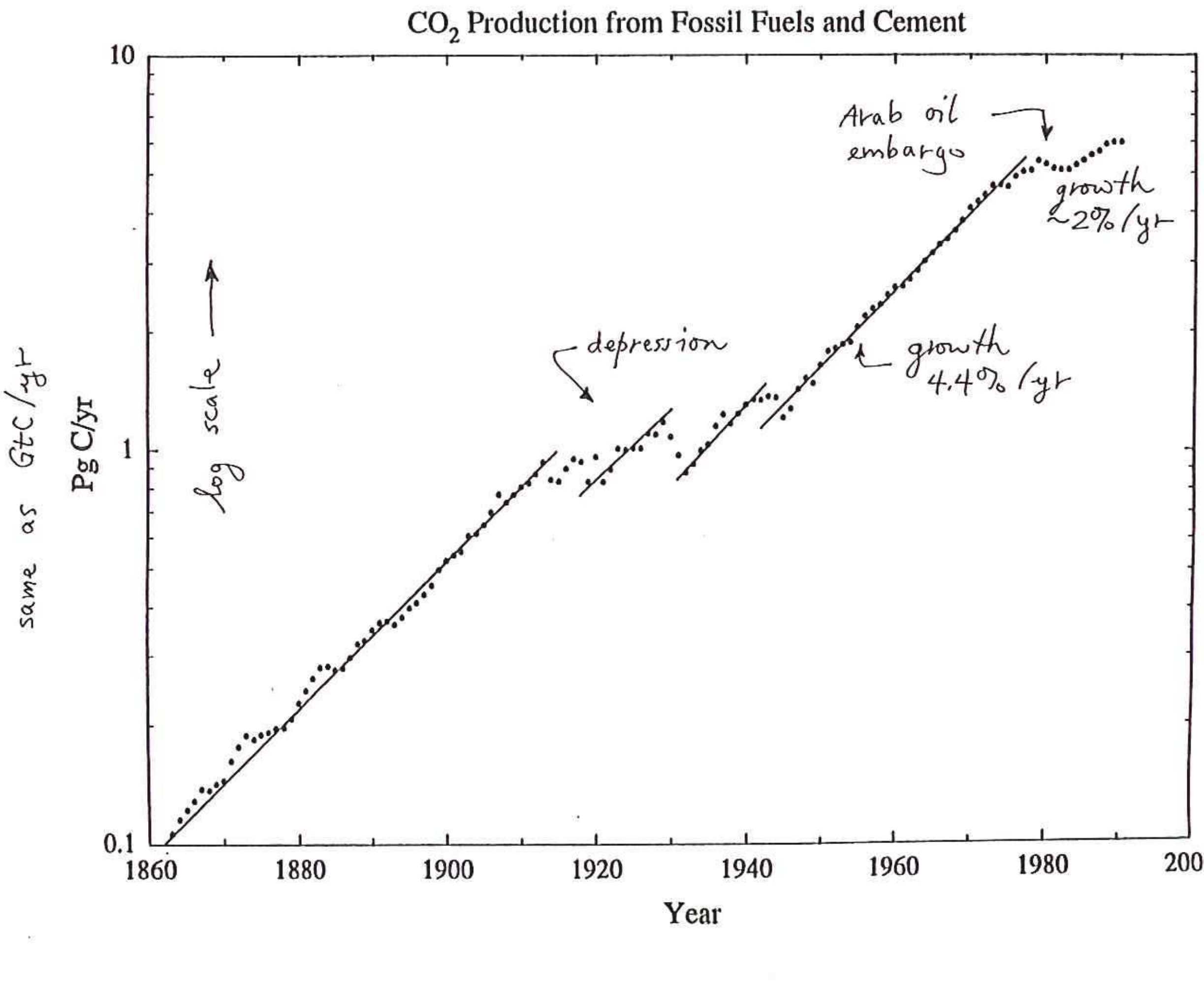


Figure 11.18. Global CO_2 emissions from fossil fuel burning and cement manufacture, 1860–1989. (From *Trends '91: A Compendium of Data on Global Change*)



The anthropogenic contribution

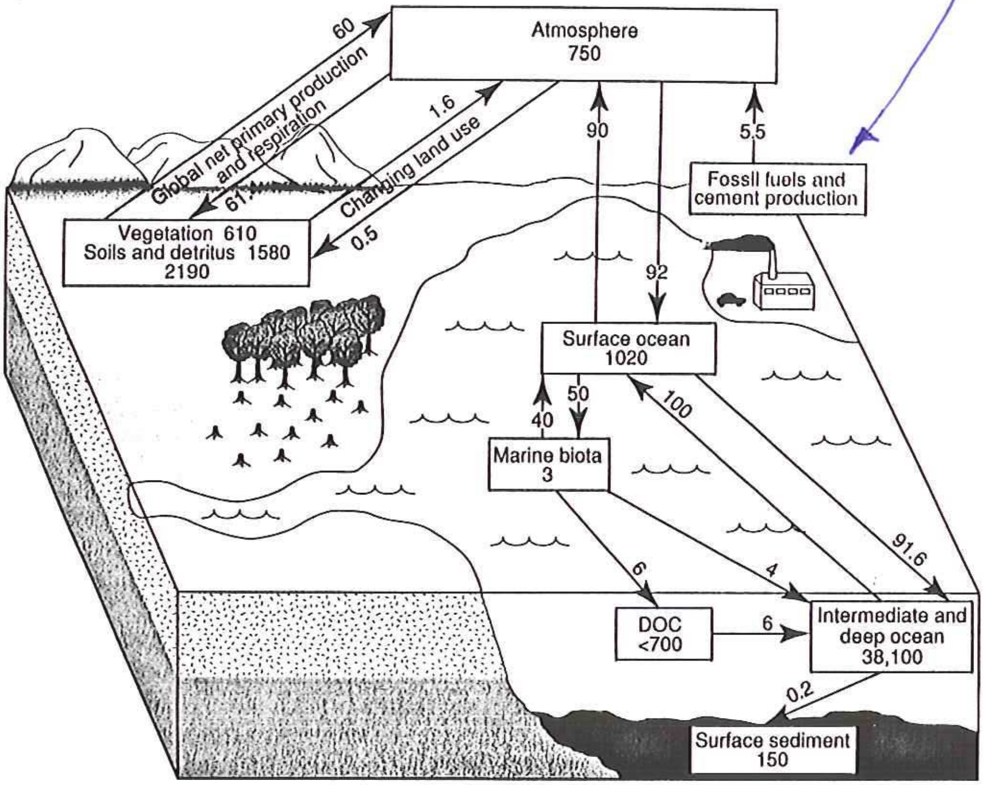
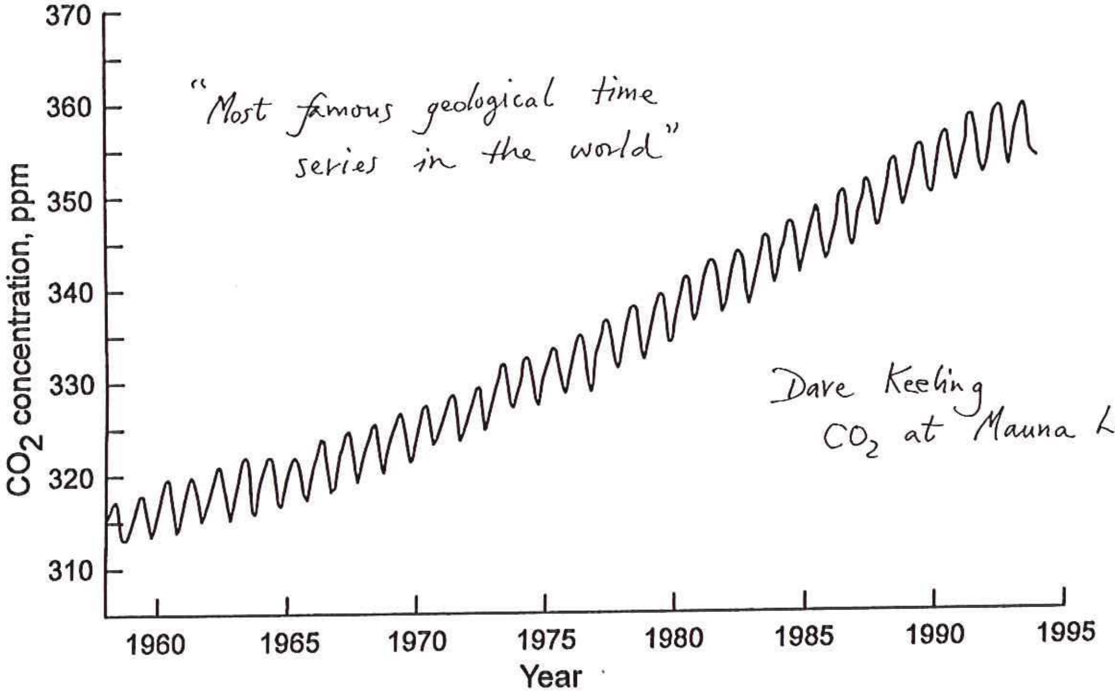


Figure 4: The global carbon cycle. The numbers in boxes indicate the size in GtC of each reservoir. On each arrow is indicated the magnitude of the flux in GtC/yr (DOC = dissolved organic carbon).



"Most famous geological time series in the world"

Dave Keeling
CO_2 at Mauna Loa

Secular increase of atmospheric CO_2 is global
1.5 ppm /yr or 0.42 % /yr

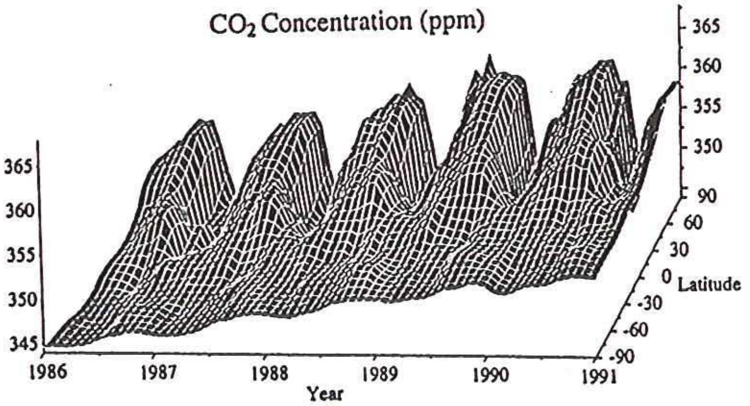
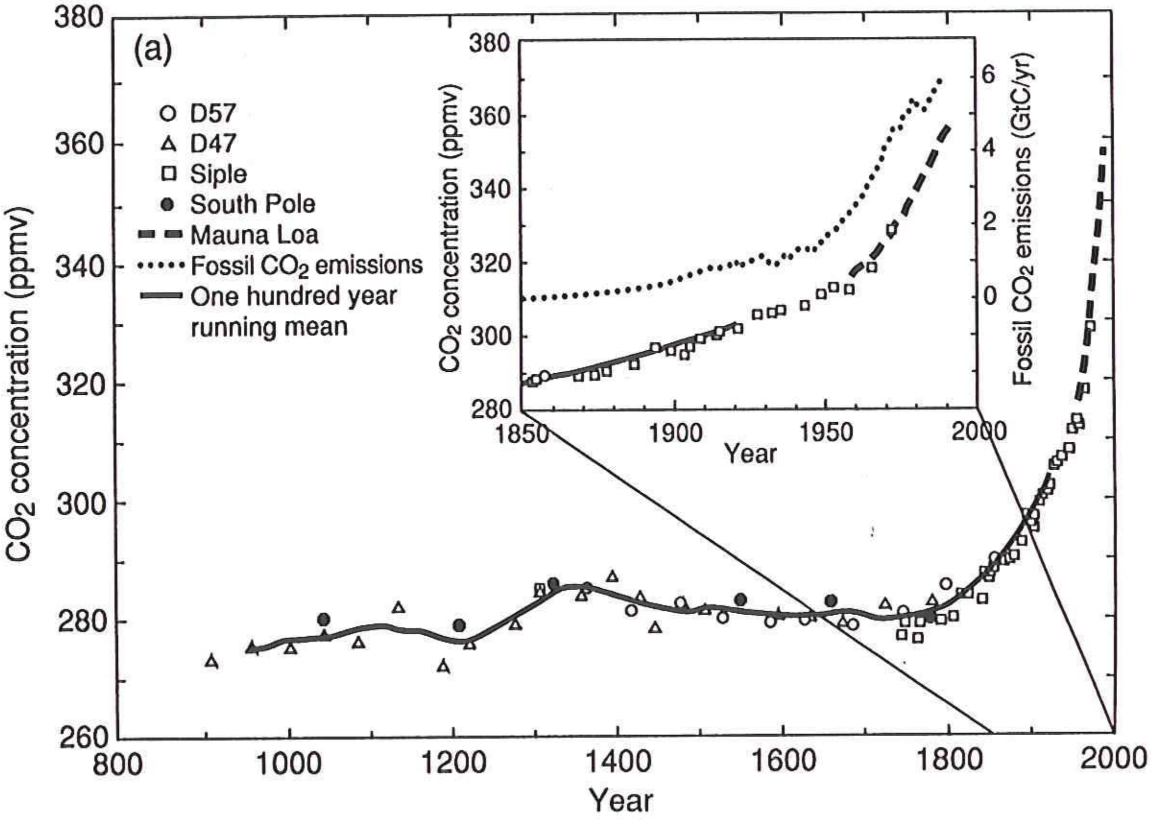


Fig. 9. Smoothed atmiospheric CO_2 data as measured by the National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory's Flask Sampling Program (Conway et al. 1991).



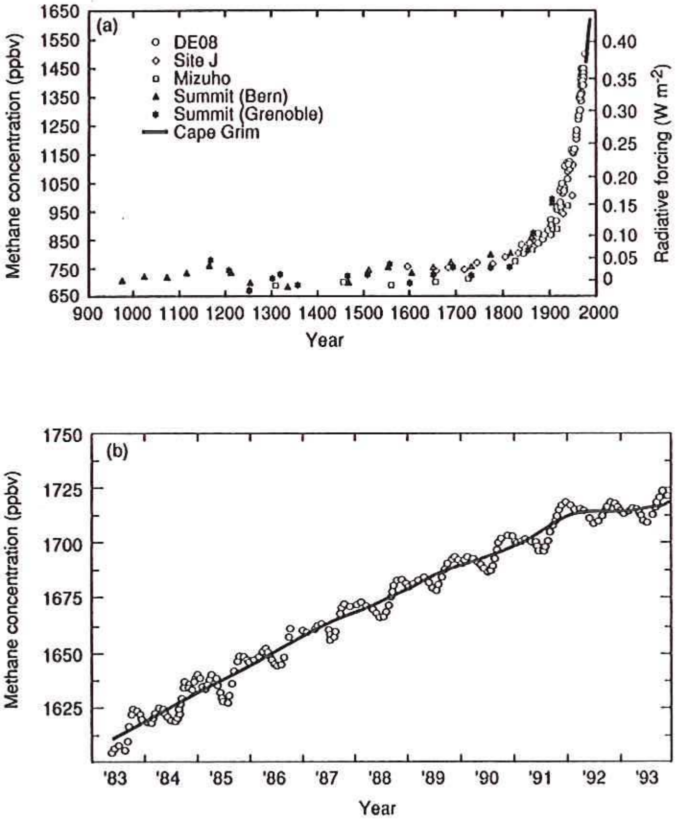
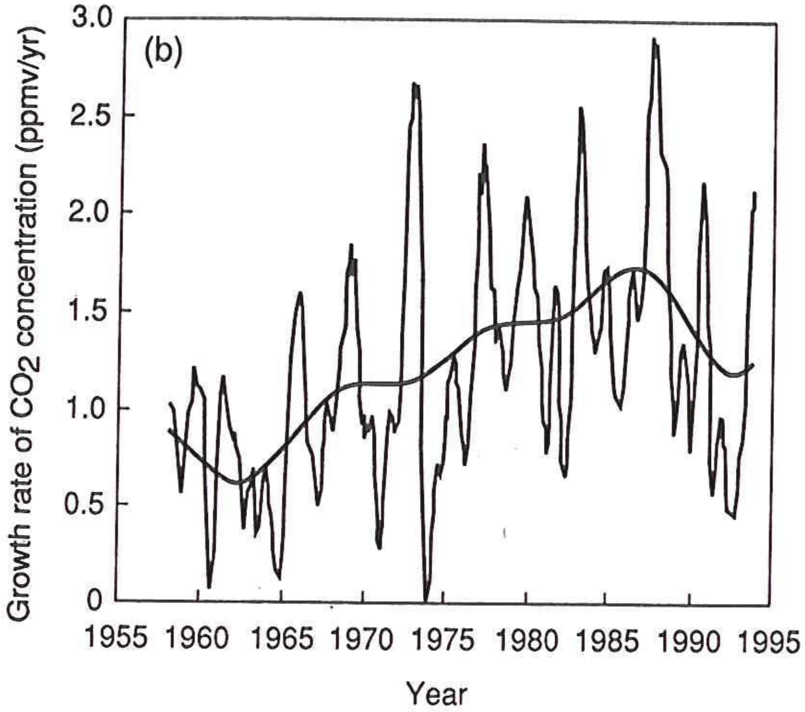


Figure 9: (a) CH_4 concentration derived from Antarctic ice cores over the past 1000 years. Direct observations of CH_4 concentration from Cape Grim, Tasmania, are included to demonstrate the smooth transition from ice core to atmospheric measurements. The radiative forcing resulting from increases in 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

ultimate

	Pre-Industrial CO_2	Ulitmate Fate of Anthropogenic CO_2
Atmosphere	1.9%	15-20%
Ocean	98.1%	80-85%

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

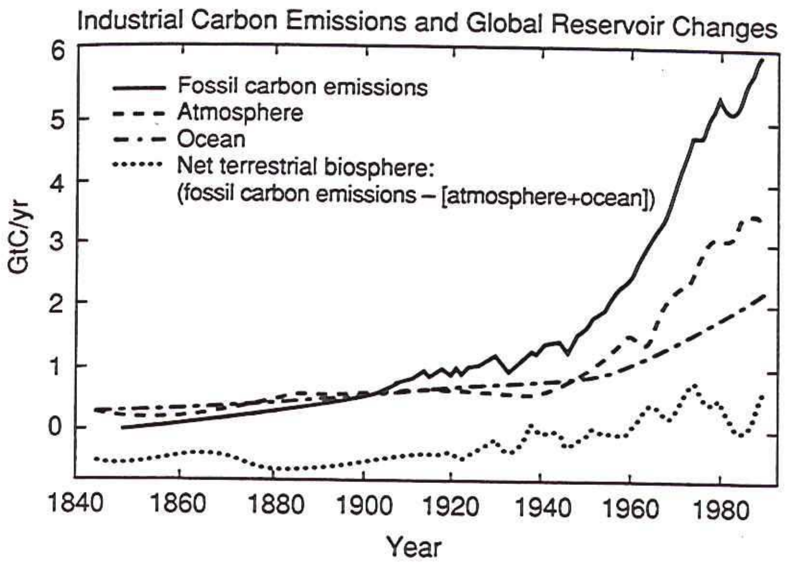


Figure 1.7: Fossil carbon emissions (based on statistics of fossil fuel and cement production), and representative calculations of global reservoir changes: atmosphere (deduced from direct observations and ice core measurements), ocean (calculated with the GFDL ocean carbon model), and net terrestrial 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.

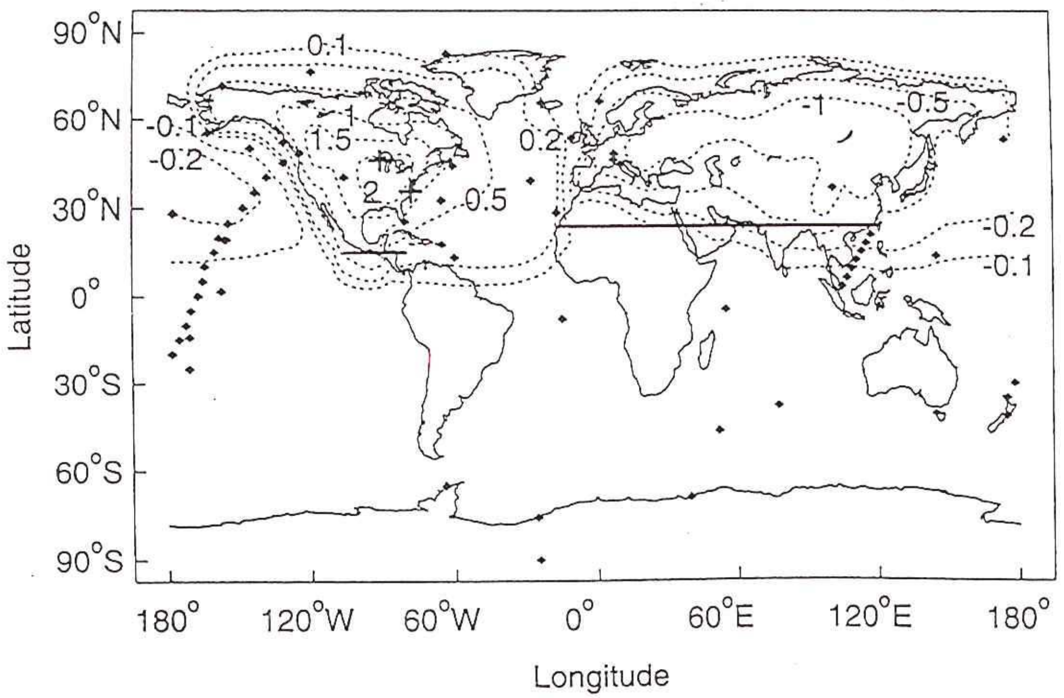


Fig. 1. A map of the atmospheric CO_2 sampling network. Sites are shown as solid diamonds. (The Globalview labels for the Northern Hemisphere stations are given in the legend of Fig. 3). The tall tower sites are shown as crosses. The thick horizontal lines divide the land surfaces into three regions 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).

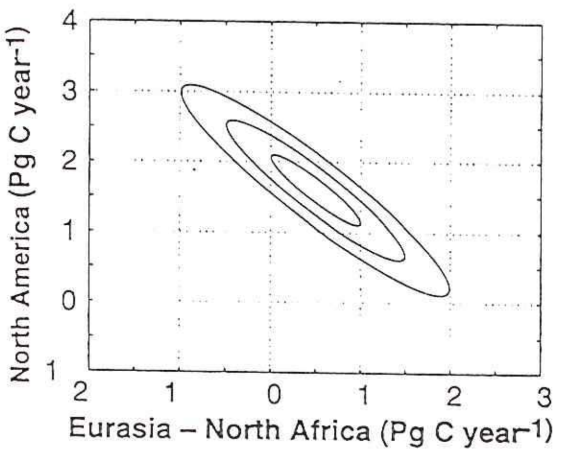


Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

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

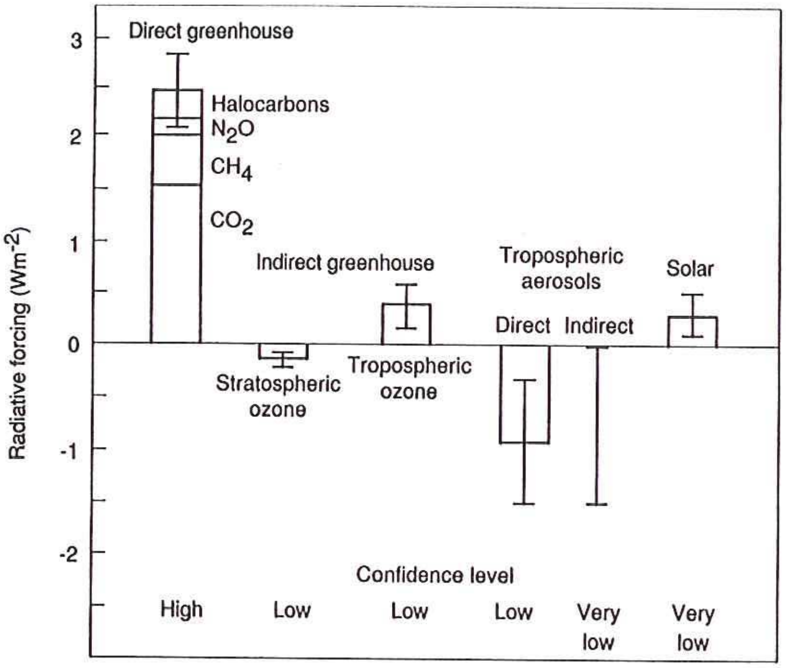


Figure 3: Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial times to the present day and changes in solar variability from 1850 to the present day. The height of the bar indicates a mid-range estimate of the forcing whilst the lines 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).

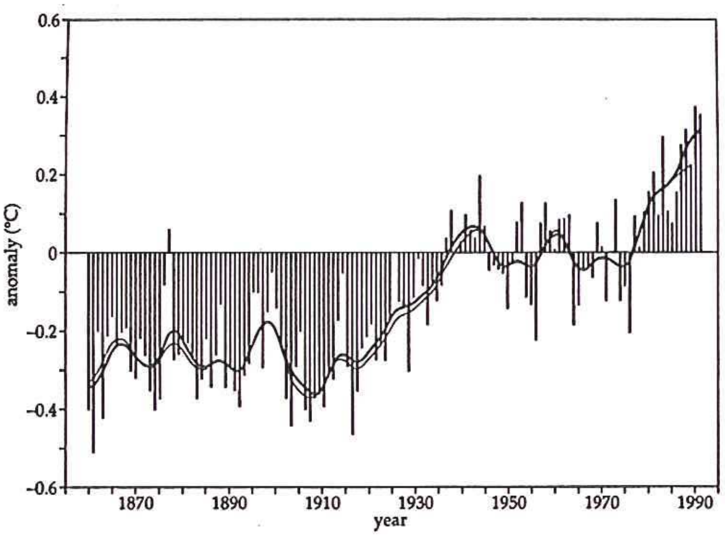
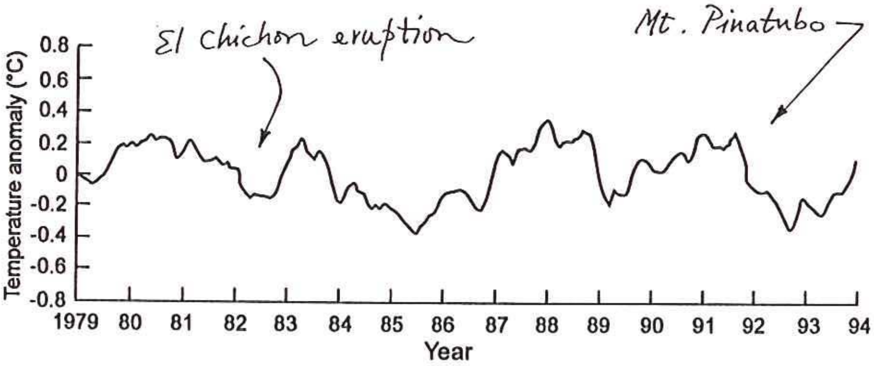


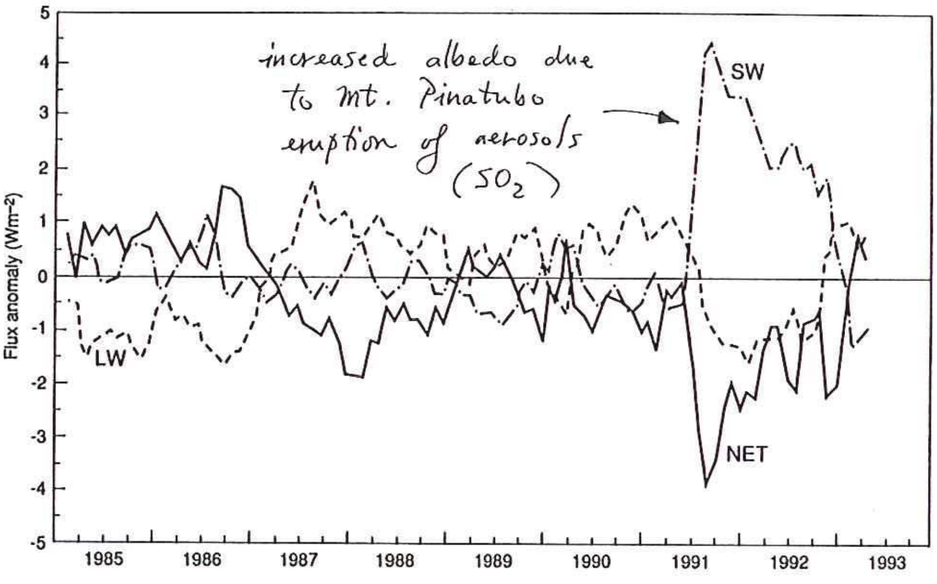
Figure 1.9 Combined land, air and sea surface temperature anomalies between 1861 and 1991, relative to the average temperature 1951–1980. (From IPCC 1992.)



El Chichon eruption

Mt. Pinatubo

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)



increased albedo due to Mt. Pinatubo eruption of aerosols (SO_2)

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.

Is there any evidence for a temperature rise?

Very difficult to measure — large geographical and temporal variability — non-uniformity of long records

Best evidence — 0.6°C rise in last century

A question of great interest is obviously — extrapolation to the future.

Question can be addressed in 2 ways.

How will atmospheric CO_2 vary for a given emission scenario?

First thing to note — atmospheric CO_2 will continue to rise even if we freeze emissions at current rate (fat chance)

Why? Slow timescale of ocean uptake

On the other hand, we can turn the problem around & ask — what must our emission rates look like if we wish to stabilize atmospheric CO_2 at a new post-boom steady-state
IPCC "Dial-a-Climate"

The total anthropogenic emission since beginning of Industrial Revolution is 300 GtC.

Natural gas is more carbon friendly than oil whereas coal and oil shale are less

[illegible]	GtC released / quad of energy
natural gas	0.015
oil	0.02
coal	0.025
oil shale	0.3 – 1.1

US dilemma : coal, our most plentiful resource, releases 1.7 times as much CO_2 / quad as natural gas

The temporal details of CO_2 emission are less important than the total amount emitted.

To stabilize atmospheric CO_2 at 2 x pre-industrial = 560 ppm we can emit no more than ~1400 GtC (in addition to the 300 GtC already emitted since Industrial Revolution)

To stabilize at current value we can emit no more than an additional ~300 GtC

Comparisons :

(1) burn all oil reserves : 2000 bbo
× 5.8 quads / bbo × 0.02 Gt/quad
= 230 GtC

(2) burn all coal reserves : 3000 Gt coal
× 28 quads / Gt coal × 0.025 GtC / quad
= 2100 GtC

At present 3.5 of 7.1 GtC/yr — 45% — of the anthropogenic emissions remain in the atmosphere.

Roughly this same percentage of future emissions will also stay in the atmosphere over the next ~ 100 years, because of the slow timescale for oceanic takeup.

If atmospheric CO_2 doubles in your lifetime, which seems very likely, then:

CO_2 rise so far from 280 ppm → 360 ppm has increased radiative forcing by 2 W/m^2.

2 × CO_2 will increase it by

$$\frac{2 \times 280}{360 - 280} = 7 \ W/m^2 \text{ increased forcing}$$

$$\frac{\Delta T}{T} = \frac{1}{4} \frac{\Delta U_0}{U_0} \qquad \Delta T = 288\ °K \times \frac{1}{4} \times \frac{7}{388}$$

$$\boxed{\Delta T = 1.3°\ K \text{ from } 2 \times CO_2}$$

None of this is in dispute. What is in dispute is what the actual ΔT will be due to feedback effects

Feedback effects of both sign are plentiful and hard to model — need to use a general circulation model = GCM

Examples:

(1) T increases ⇒ increased oceanic evaporation — H_2O absorbs IR ⇒ increased warming

(2) But increased evaporation ⇒ more clouds — this increases the albedo ⇒ decreased warming

A leading modeler — Suke Manabe of Princeton GFDL — his model of Earth climate in equilibrium with $2 \times CO_2 = 720$ ppm:

- surface warming by 1.5° – 4.5°C "best" estimate 2.5°C
- cooling in stratosphere
- polar warming > temperate
- warming of mixed layer in ocean — little change in deep ocean
- increased precipitation
- climate extremes will increase — not only it will be warmer on average in Princeton (2.5°C = 4.5°F) but there will be more extremely hot days
- rise in sea level by ~50 cm

Climate Change Record in Subsurface Temperatures: A Global Perspective

Henry N. Pollack,* Shaopeng Huang, Po-Yu Shen

Analyses of underground temperature measurements from 358 boreholes in eastern North America, central Europe, southern Africa, and Australia indicate that, in the 20th century, the average surface temperature of Earth has increased by about 0.5°C and that the 20th century has been the warmest of the past five centuries. The subsurface temperatures also indicate that Earth's mean surface temperature has increased by about 1.0°C over the past five centuries. The geothermal data offer an independent confirmation of the unusual character of 20th-century climate that has emerged from recent multiproxy studies.

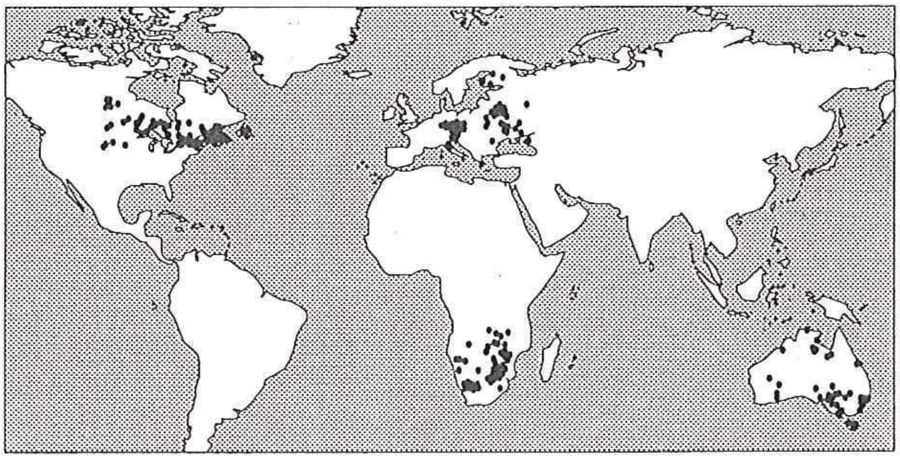
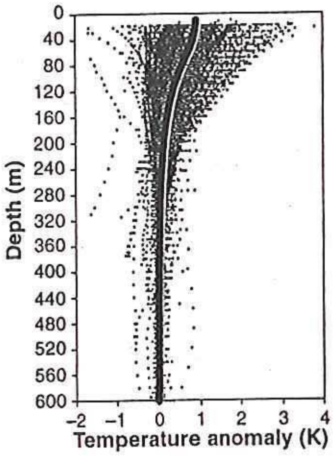


Fig. 1. Locations of 358 boreholes, whose subsurface temperature measurements were analyzed to reconstruct a surface temperature history. There are 116 sites in eastern North America, 98 in central Europe, 86 in southern Africa, and 58 in Australia.



Borehole reconstruction of past temperatures. Red lines: subsurface temperature anomalies. Thick black line: average temperature anomaly. The vertical profile of the temperature anomaly depends on the history of energy balance at the surface. The area formed by the departure from the steady state (zero in the horizontal axis) from the surface to ~350 m provides a rough estimate of the total heat absorbed by the ground during the last 500 years. The anomalies indicate warming in most areas, but a few negative anomalies point to ground cooling in some areas (*19*).

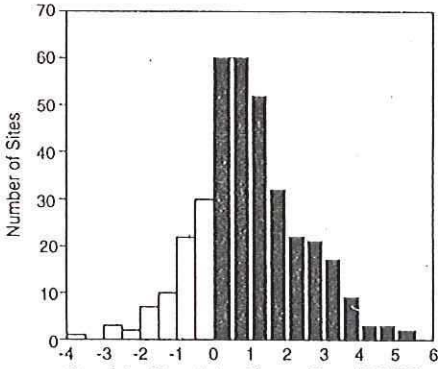


Fig. 2. Histogram of cumulative five-century temperature changes at sites shown in Fig. 1. Black columns indicate net warming and white columns indicate net cooling.

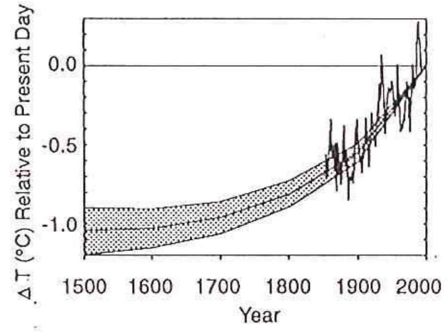


Fig. 3. Composite four-region surface temperature change over the past five centuries, relative to the present, as determined from geothermal data. Shaded areas represent ±1 standard error about the mean history. Superimposed is a smoothed (5-year running average) SAT instrumental record (*10*) representing a composite of the same regions as the geothermal data. Because the SAT series is referenced to the mean anomaly over the interval from 1961 to 1990 and because the geothermal result is referenced to the present, we have shifted the SAT series downward by 0.2°C to enable a visual comparison of the trends by a direct overlay.

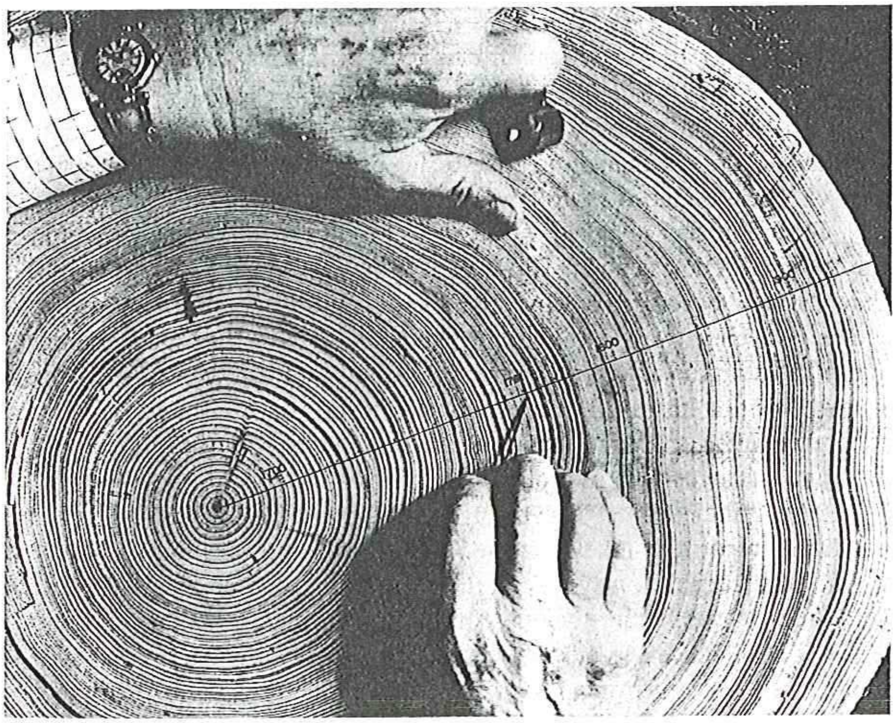
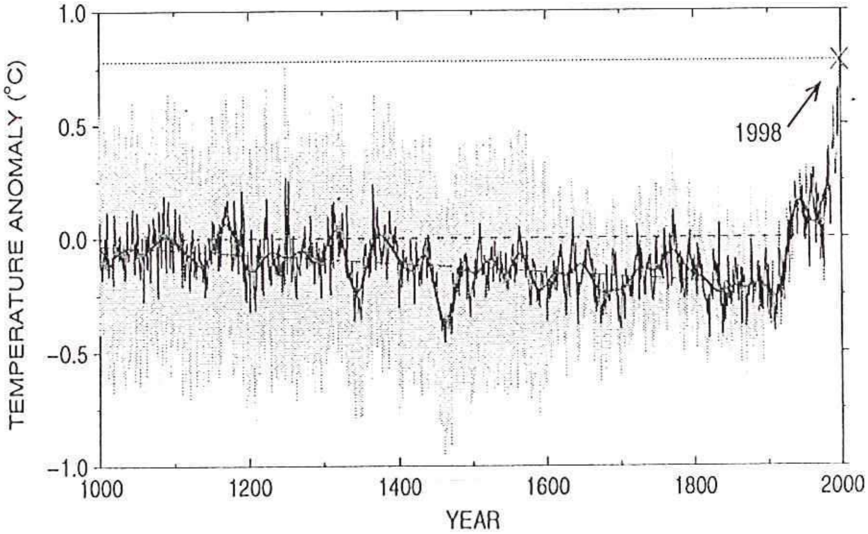


FIGURE 2–1 A cross section of the trunk of a Douglas fir shows the method of dating tree rings *(dendrochronology)*. The annual variability of ring widths in this species provides a record of climate change during the life of the tree. (Photograph courtesy of the Laboratory of Tree-Ring Research, the University of Arizona.)



Warming of the World Ocean

Sydney Levitus,* John I. Antonov, Timothy P. Boyer, Cathy Stephens

We quantify the interannual-to-decadal variability of the heat content (mean temperature) of the world ocean from the surface through 3000-meter depth for the period 1948 to 1998. The heat content of the world ocean increased by ~2 × 10^{23} joules between the mid-1950s and mid-1990s, representing a volume mean warming of 0.06°C. This corresponds to a warming rate of 0.3 watt per meter squared (per unit area of Earth's surface). Substantial changes in heat content occurred in the 300- to 1000-meter layers of each ocean and in depths greater than 1000 meters of the North Atlantic. The global volume mean temperature increase for the 0- to 300-meter layer was 0.31°C, corresponding to an increase in heat content for this layer of ~10^{23} joules between the mid-1950s and mid-1990s. The Atlantic and Pacific Oceans have undergone a net warming since the 1950s and the Indian Ocean has warmed since the mid-1960s, although the warming is not monotonic.

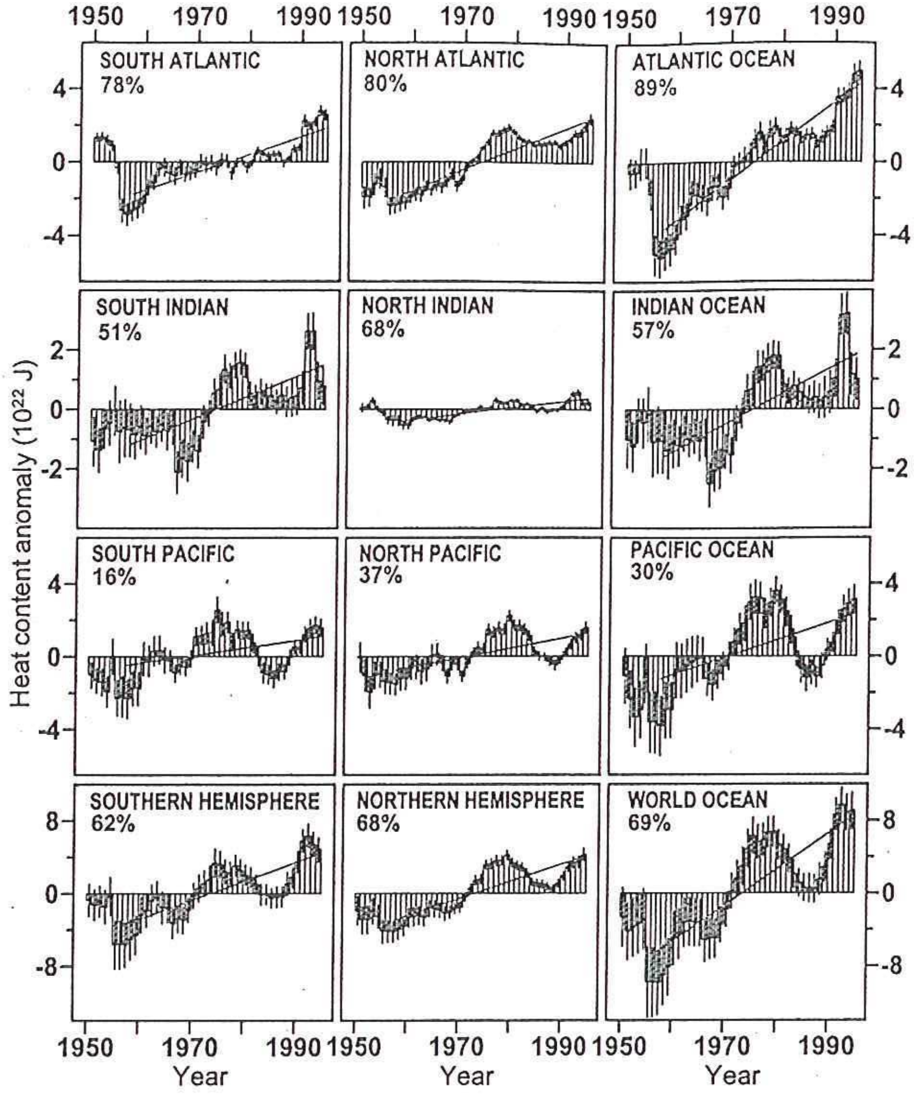


Fig. 4. Time series of 5-year running composites of heat content (10^{22} J) in the upper 3000 m for each major ocean basin. Vertical lines represent ±1 SE of the 5-year mean estimate of heat content. The linear trend is estimated for each time series for the period 1955 to 1996, which corresponds to the period of best data coverage. The trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel. Expanded versions of these figures with equivalent volume mean temperature scales added can be viewed at *Science* Online (*14*).

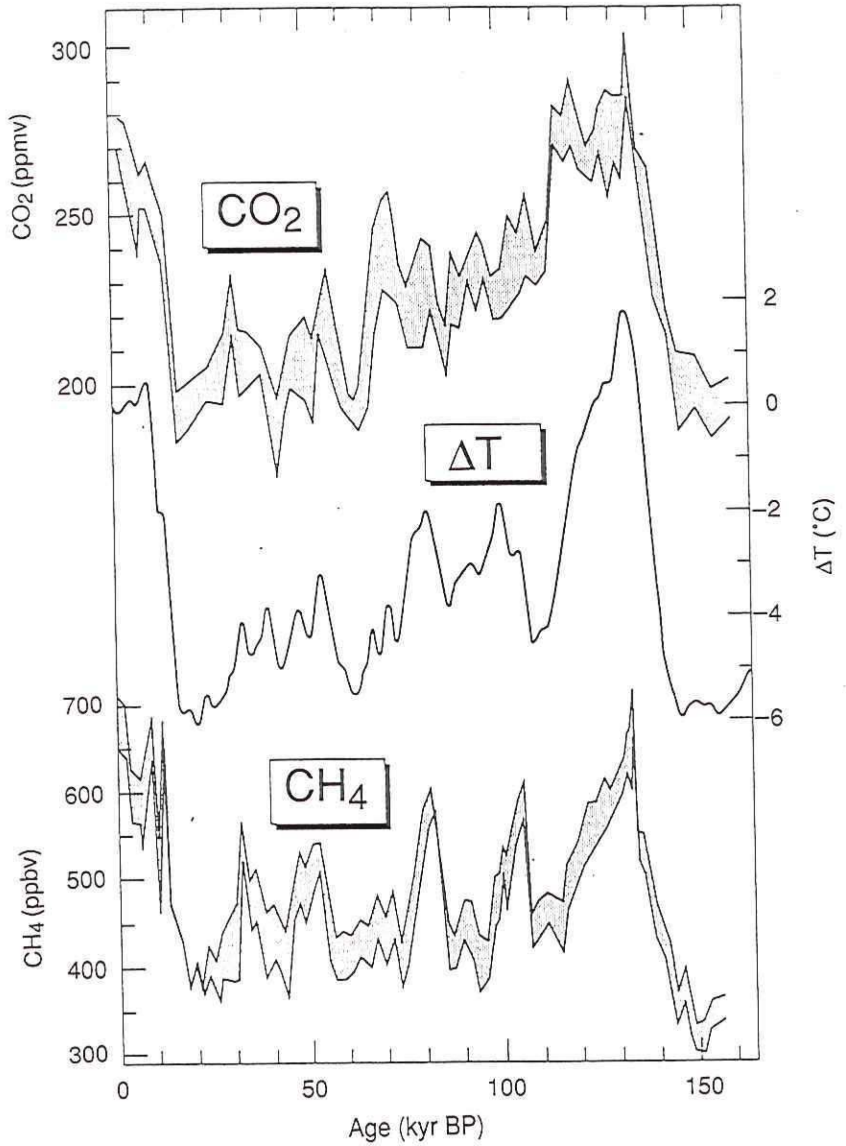


Figure 1.4 Antarctic ice core records of local atmospheric temperature and atmospheric carbon dioxide and methane volume mixing ratios for the past 160,000 years. (Mixing ratios and other units are discussed in the appendix on units of measurement.) Note that for most of the period temperatures were lower than the present world average (denoted as ΔT = 0 at 0 Kyr BP). The present warm period (interglacial) started some 20,000 years ago. The previous period with comparable temperatures occurred between 120 and 140 kyr BP. (C. Lorius, private communication, 1990.)

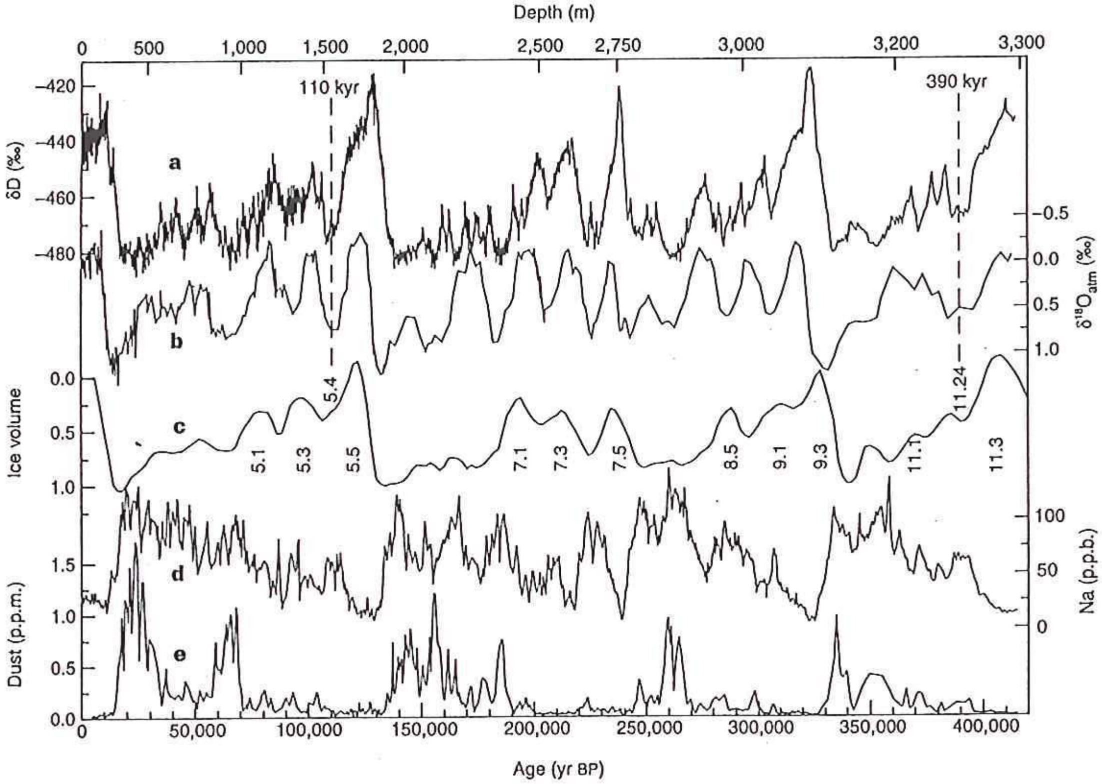


Figure 2 Vostok time series and ice volume. Time series (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis and indication of the two fixed points at 110 and 390 kyr) of: **a**, deuterium profile (from Fig. 1); **b**, $\delta^{18}O_{atm}$ profile obtained combining published data[11,13,30] and 81 new measurements performed below 2,760 m. The age of the gas is calculated as described in ref. 20; **c**, seawater $\delta^{18}O$ (ice volume proxy) and marine isotope stages adapted from Bassinot *et al.*[28]; **d**, sodium profile obtained by combination of published and new measurements (performed both at LGGE and RSMAS) with a mean sampling interval of 3–4 m (ng g^{-1} or p.p.b); and **e**, dust profile (volume of particles measured using a Coulter counter) combining published data[10,13] and extended below 2,760 m, every 4 m on the average (concentrations are expressed in $\mu g\, g^{-1}$ or p.p.m. assuming that Antarctic dust has a density of 2,500 kg m^{-3}). $\delta^{18}O_{atm}$(in ‰) $= [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1] \times 1{,}000$; standard is modern air composition.

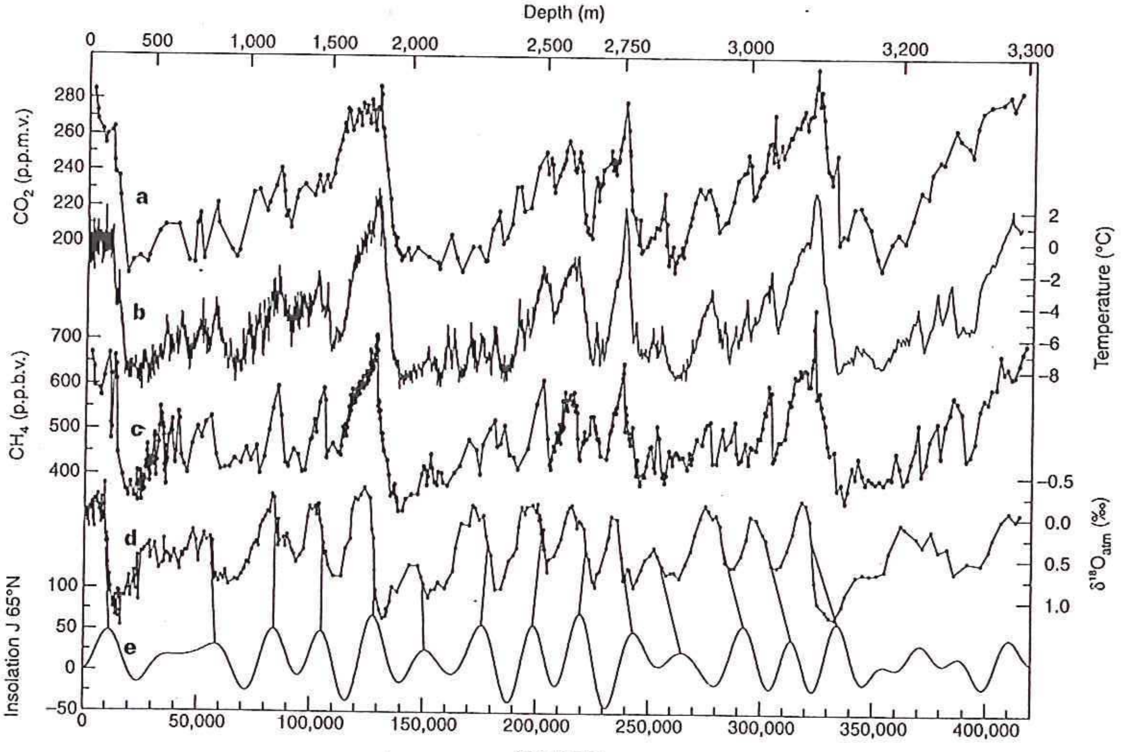


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June insolation at 65° N (in W m^{-2}) (ref. 3). CO_2 and CH_4 measurements have been performed using the methods and analytical procedures previously described[5,9]. However, the CO_2 measuring system has been slightly modified in order to increase the sensitivity of the CO_2 detection. The thermal conductivity chromatographic detector has been replaced by a flame ionization detector which measures CO_2 after its transformation into CH_4. The mean resolution of the CO_2 (CH_4) profile is about 1,500 (950) years. It goes up to about 6,000 years for CO_2 in the fractured zones and in the bottom part of the record, whereas the CH_4 time resolution ranges between a few tens of years to 4,500 years. The overall accuracy for CH_4 and CO_2 measurements are ±20 p.p.b.v. and 2–3 p.p.m.v., respectively. No gravitational correction has been applied.

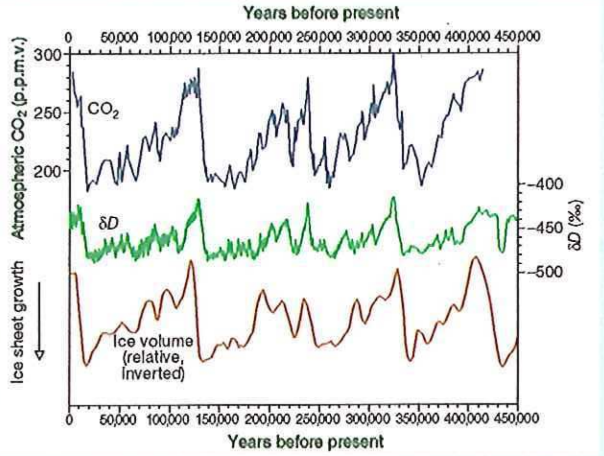


Figure 1 The history of atmospheric CO_2 back to 420 kyr ago as recorded by the gas content in the Vostok ice core from Antarctica[4]. The ratio of deuterium to hydrogen in ice (expressed as the term δD) provides a record of air temperature over Antarctica, with more negative δD values corresponding to colder conditions. The history of global ice volume based on benthic foraminiferal oxygen isotope data from deep-sea sediment cores[96] is plotted as relative sea level, so that ice ages (peaks in continental ice volume) appear as sea level minima, with a full glacial/interglacial amplitude for sea level change of about 120 m (ref. 18). During peak glacial periods, atmospheric CO_2 is 80–100 p.p.m.v. lower than during peak interglacial periods, with upper and lower limits that are reproduced in each of the 100-kyr cycles. Ice core records, including the Vostok record shown here, indicate that atmospheric CO_2 was among the early parameters to change at the termination of glacial maxima, roughly in step with Southern Hemisphere warming and preceding the decline in Northern Hemisphere ice volume.

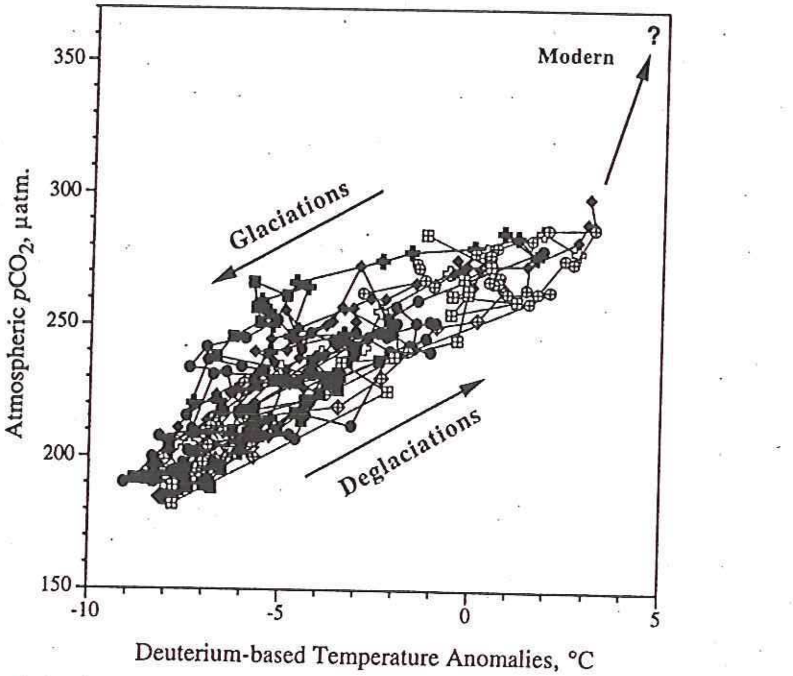


Fig. 1. A correlation between atmospheric partial pressure of CO_2 (pCO_2) and isotopic (δ_D) temperature anomalies as recorded in the Vostok ice core. The figure shows that climate variations in the past 420,000 years operated within a relatively constrained domain. Data are from (8).

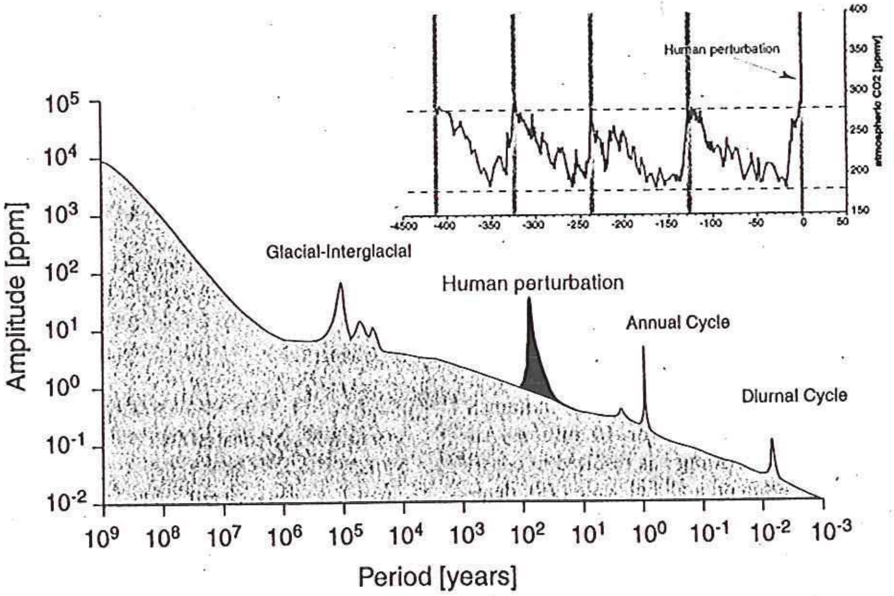


Fig. 2. Schematic variance spectrum for CO_2 over the course of Earth's history. Note the impact of human perturbations on the decade-to-century scale. **(Inset)** Changes in atmospheric CO_2 over the past 420,000 years as recorded in the Vostok ice, showing that both the rapid rate of change and the increase in CO_2 concentration since the Industrial Revolution are unprecedented in recent geological history.

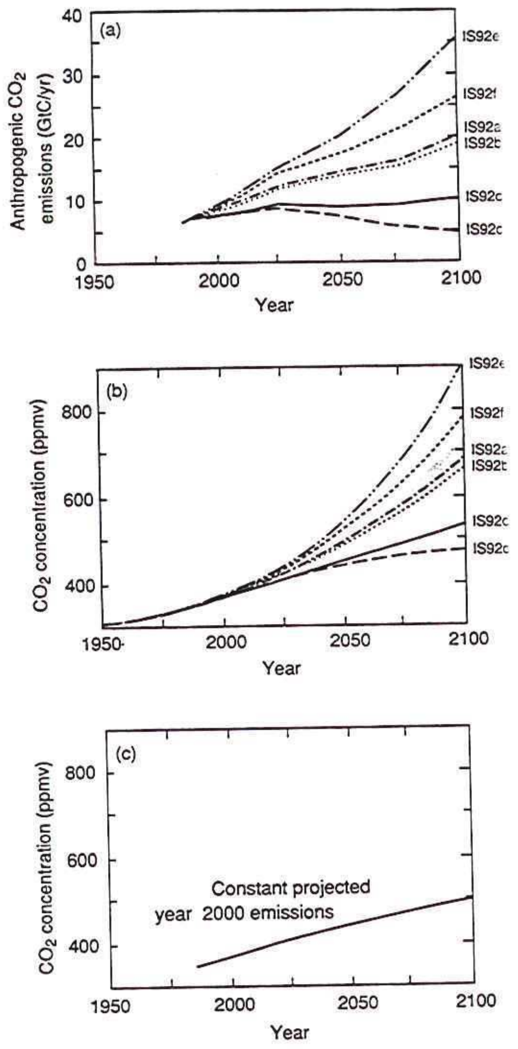


Figure 5: (a) Prescribed anthropogenic emissions of CO_2 (from fossil fuel use, deforestation and cement production) for the IS92 Scenarios, (b) CO_2 concentrations resulting from the IS92 emission scenarios calculated using the "Bern" model, a mid-range carbon cycle model (a range of results from different models is indicated by the shaded area of the IS92a curve) and (c) CO_2 concentrations resulting from constant projected year 2000 emissions (using the model of Wigley).

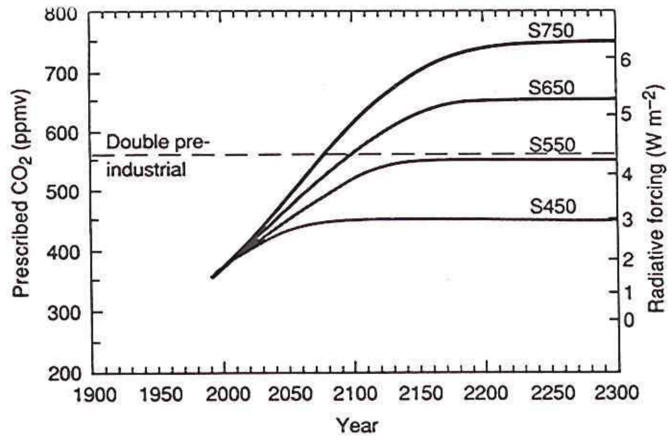


Figure 6: Profiles of atmospheric CO_2 concentration leading to stabilisation at 350, 450, 550, 650 and 750 ppmv. Doubled pre-industrial CO_2 concentration is 560 ppmv. The radiative forcing resulting from the increase in CO_2 relative to pre-industrial levels is marked on the right-hand axis. Note the non-linear nature of the relationship between CO_2 concentration change and radiative forcing.

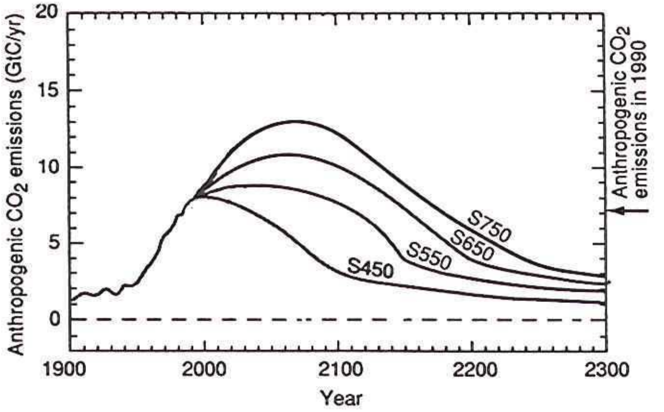


Figure 7: Illustrative anthropogenic emissions of CO_2 leading to stabilisation at concentrations of 350, 450, 550, 650 and 750 ppmv following the profiles shown in Figure 6 (using a mid-range carbon cycle model). The range of results from different models is indicated on the 450 ppmv profile. The emissions for the IS92a, c and e Scenarios are also shown on the figure. The negative emissions for stabilisation at 350 ppmv are an artefact of the particular concentration profile imposed.

300 GtC
total
anthropogenic
emission
since Industrial
Revolution

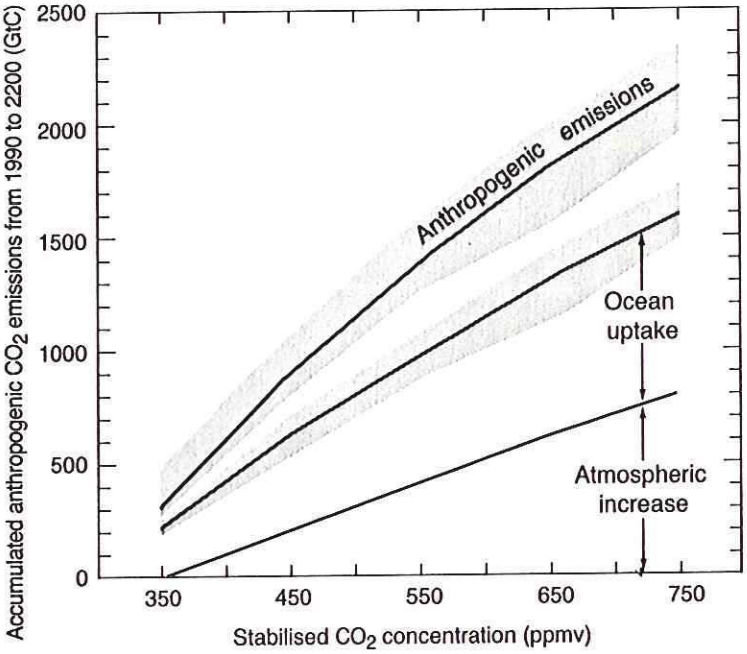


Figure 1.14: Accumulated anthropogenic CO_2 emissions over the period 1990 to 2200 (GtC) plotted against the final stabilised concentration level. Also shown are the accumulated ocean uptake and the increase of CO_2 in the atmosphere. The curves for accumulated anthropogenic emissions and ocean uptake were calculated using the model of Siegenthaler and Joos (1992). The shaded areas show the spread of results from a range of carbon cycle model calculations. The difference (i.e., the accumulated anthropogenic emissions minus the total of the atmospheric increase and the accumulated ocean uptake) gives the cumulative change in terrestrial biomass.

Table 11. Carbon dioxide emission rates for different fuels [in kg °C (in CO_2) per million BTU energy].

Fuel	kg C per MBTU[a]	Adopted[b]	GtC/quad
Natural gas	14–15	14.5	0.015
Liquid fuels from crude oil	19–22	20.3	0.02
Bituminous coal	25	25.1	0.025
Shale oil	30–110		0.03–0.11
Liquids from coal	32–54		
High BTU gas from coal	34–43		

[a] From G. Marland, in Ref. 44.

[b] Used in IEA/ORAU model (32), p. 266.

Possible feedbacks amplifying the greenhouse effect

- A reduction in northern hemisphere snow cover and/or a melting of part of the Arctic ice sheet. This will reduce the earth's albedo (capacity to reflect solar radiation) thereby increasing temperature further.
- A release of methane currently locked in permafrost in the Arctic; this acts as a greenhouse gas.
- An increase in the rate of decomposition of organic matter in soils and peat, releasing additional CO_2 into the atmosphere.
- More evaporation leading to an increase in the concentration of water vapour in the atmosphere, which acts as a greenhouse gas.
- An increase in the rate of respiration in plants and animals releasing CO_2 currently resident in the living biota of the world.

Possible feedbacks decreasing the greenhouse effect

- More evaporation results in greater cloud cover, increasing the earth's albedo and thereby reducing the temperature.
- More evaporation increases polar precipitation of snow, which increases the earth's albedo.
- The increased concentration of CO_2 in the atmosphere stimulates photosynthesis globally, which sequesters more carbon in the biosphere.

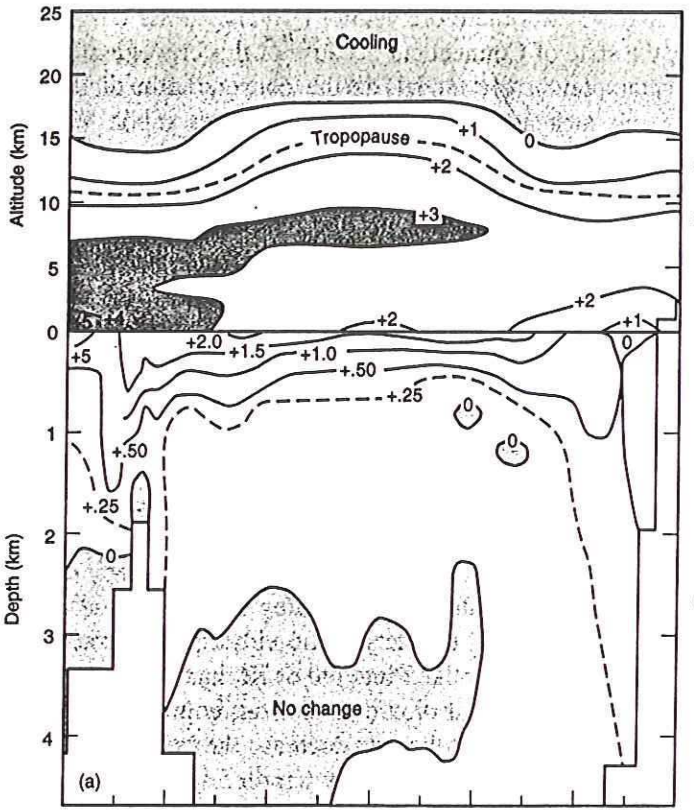


FIGURE 7–4 The changes in atmospheric and oceanic temperatures (in degrees Celsius) predicted by a general circulation model (GCM) for a doubling of the CO_2 concentration in the atmosphere from the present value based on a coupled ocean-atmosphere model. The projected doubling of CO_2 will occur in less than 100 years. Note that warming is not the same at all latitudes and that cooling occurs in the stratosphere. The major warming of the ocean is above 1 kilometer. (Modified after S. Manabe, R. J. Stouffer, and M. J. Spelman, 1994, *Ambio,* v. 23, p. 44.)

APPENDIX 7–3: POSSIBLE EFFECTS ON THE ENVIRONMENT INFERRED FROM CLIMATE MODELS[1]

Virtually Certain

1. Large stratospheric cooling will result from the increase in CO_2 concentration and ozone depletion; the start of such cooling has been predicted by models and observed in the upper stratosphere.

Very Probable

2. Global mean surface temperature warming will increase by the mid-twenty-first century. The best available estimate is that global mean surface temperatures will increase by about 0.5 to 2°C (or about 1 to 3.5°F) over the period from 1990 to 2050 due to increases in the concentrations of greenhouse gases alone (note that point 15 indicates it is inappropriate to convert these estimates to a per-decade basis), assuming no significant actions to reduce the projected increase in the rate of emissions of these gases. The best available estimate for a climate change that is in equilibrium with two times the pre-industrial carbon dioxide concentration (or equivalent in terms of other greenhouse gases) is a warming of 1.5 to 4.5°C, with 2.5°C being the most probable estimate.
3. Global mean precipitation will increase. The distribution of this change is less certain.
4. Northern hemisphere sea ice will be reduced (the magnitude of the change will depend on the amount of the warming, and the reduced extent will initially be most evident in the transition seasons). Projected changes and their timing in the southern hemisphere sea-ice extent are less certain.
5. Arctic land areas will experience wintertime warming.
6. Global sea level will rise at an increasing rate, although with some probability that the rate of rise may not be significantly greater than at present. The most reasonable estimates for the rate of sea-level rise are for a rise of 5–40 cm by 2050, as compared to a rise of 5–12 cm if rates of rise over the past century continue.
7. Solar variability over the next 50 years will not induce a prolonged forcing that is significant in comparison with the effects of the increasing concentrations of CO_2 and other greenhouse gases.

Probable

8. Summer northern hemisphere mid-latitude continental dryness will increase.
9. High-latitude precipitation will increase, with potential feedback effects related to the influence of additional freshwater on the thermohaline circulation and of increased snowfall or rain on the mass balance of polar ice caps.
10. Antarctic and North Atlantic ocean regions will experience warming that is slower than the global average.
11. Transient explosive volcanic eruptions will result in short-term relative cooling.

Uncertain

12. Changes in climate variability will occur. As yet there is no clear evidence that suggests how the character of interannual variability may change due to greenhouse warming, but there is the potential for multifaceted and complicated, even counter-intuitive, changes in variability.
13. Regional scale (100–2000 km) climate changes will be different from the global average changes. However, at present there is only very limited capability to estimate how various regions will respond to global climate change.
14. Tropical storm intensity may change.
15. Details of the climate change over the next 25 years are uncertain.
16. Biosphere-climate feedbacks are expected, but how much these feedbacks will amplify or moderate climate change is uncertain.

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[1] From *U.S. Global Change Research Program Report 95-02*, July 1995, report chaired by E. Barron.

Uncertainties in Projections of Human-Caused Climate Warming

J. D. Mahlman

Mankind's activities have increased carbon dioxide (CO_2) in the atmosphere. This increase has the potential to warm the earth's climate by the "greenhouse effect" (*1*) in which CO_2 absorbs infrared radiation and then re-radiates it back toward the surface of the planet. Other gases also act as greenhouse gases and may warm the climate even further (*2*), although human-produced airborne sulfate particles can cause cooling that offsets some of the warming (*3*). Computational models that include these factors predict that the climate will warm significantly over the next century.

These forecasts of likely climate changes have forced a realization that it is necessary to reduce human-caused emissions of greenhouse gases. But because of the potential social disruptions and high economic costs of such reductions, vigorous debate has arisen about the size and nature of the projected climate changes and whether they will actually lead to serious impacts.

A key element of these spirited—and often acrimonious—debates is the credibility (or lack thereof) of the mathematically and physically based climate models (*4*) that are used to project the climate changes resulting from a sustained buildup of atmospheric CO_2. Some skeptics ask, to put it bluntly, why should we believe such models' attempts to describe changes in such a dauntingly complex system as Earth's climate? The cheap answer is that there are no credible alternatives. But the real answer is that the climate models do a reasonably good job of capturing the essence of the large-scale aspects of the current climate and its considerable natural variability on time scales ranging from 1 day to decades (*4*). In spite of these considerable successes, the models contain weaknesses that add important uncertainty to the very best model projections of human-induced climate changes.

I express here a "policy-independent" evaluation of the levels of current scientific confidence in predictions emanating from climate models. This climate model uncertainty is distinct from the high social uncertainty associated with future scenarios of greenhouse gas and airborne particle concentrations. I assume that detailed future greenhouse and airborne particle scenarios are part of the policy question and thus do not discuss them further.

A fair-minded and exhaustive attempt to find a broad consensus on what science can say about this problem is contained in the most recent 1996 IPCC Working Group I Assessment (*3*). Some of my evaluations differ in detail from those of IPCC 1996, mostly because of the addition of new research insights and information since 1994. A good guideline for evaluating contrary "expert" opinions is whether they use the IPCC science as a point of departure for their own analysis. In effect, if we disagree scientifically with IPCC, we should explain why. Without such discipline, contrary arguments are not likely to be scientifically sound.

Virtually Certain "Facts"

These key aspects of our knowledge of the climate system do not depend directly on the skill of climate model simulations and projections:

- Atmospheric abundances of greenhouse gases are increasing because of human activities.
- Greenhouse gases absorb and re-radiate infrared radiation efficiently. This property acts directly to heat the planet.
- Altered amounts of greenhouse gases affect the climate for many centuries. The major greenhouse gases remain in the atmosphere for periods ranging from a decade to centuries. Also, the climate itself has considerable inertia, mainly because of the high heat capacity of the world ocean.
- Changes in other radiatively active substances offset somewhat the warming effect of increased greenhouse gases. Observed decreases in lower stratospheric ozone and increases in sulfate particles both produce cooling effects. The cooling effect of sulfate particles remains insufficiently quantified.
- Human-caused CO_2 increases and ozone decreases in the stratosphere have already produced more than a 1°C global average cooling there. This stratospheric cooling is generally consistent with model predictions.
- Over the past century, Earth's surface has warmed by about 0.5°C (±0.2°C).
- The natural variability of climate adds confusion to the effort to diagnose human-induced climate changes. Apparent long-term trends can be artificially amplified or damped by the contaminating effects of undiagnosed natural variations.
- Significant reduction of key uncertainties will require a decade or more. The uncertainties concerning the responses of clouds, water vapor, ice, ocean currents, and specific regions to increased greenhouse gases remain formidable.

I further illustrate these climate uncertainties using two extrapolations of the IPCC idealized scenarios of increases of 1% equivalent atmospheric CO_2 concentration per year (*5*). The first case levels off at a CO_2 doubling after 70 years; the second levels off at a CO_2 quadrupling after 140 years. Both correspond to simple extrapolations of current trends in greenhouse gas emissions. Considering the long residence time of CO_2 at such large concentrations, these leveled-off scenarios are physically plausible but are presented as illustrations, not as social predictions.

Virtually Certain Projections

These projections have a greater than 99 out of 100 chance of being true within the predicted range (*6*):

- The stratosphere will continue to cool significantly as CO_2 increases. If ozone continues to decrease, the cooling will be magnified. There is no known mechanism to prevent the global mean cooling of the stratosphere under these scenarios.
- Global mean amounts of water vapor will increase in the lower troposphere (0 to 3 km) in approximately exponential proportion (roughly 6% per 1°C of warming) to the global mean temperature change. The typical relative humidities would probably change substantially less, in percentage terms, than would water vapor concentrations.

Very Probable Projections

These projections have a greater than 9 out of 10 chance of being true within the predicted range:

- The global warming observed over the past century is generally consistent with *a posteriori* model projections of expected greenhouse warming, if a reasonable sulfate particle offset is included. It is difficult, but not impossible, to construct conceivable alternate hypotheses to explain this observed warming. Using variations in solar output or in natural climate to explain the observed warming can be appealing, but both have serious logical inconsistencies.
- A doubling of atmospheric CO_2 over preindustrial levels is projected to lead to an equilibrium global warming in the range of 1.5° to 4.5°C. These generous uncertainty brackets reflect remaining limitations in modeling the radiative feedbacks of clouds,

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details of the changed amounts of water vapor in the upper troposphere (5 to 10 km), and responses of sea ice. In effect, this means that there is roughly a 10% chance that the actual equilibrium warming caused by doubled atmospheric CO_2 levels could be lower than 1.5°C or higher than 4.5°C. For the answer to lie outside these bounds, we would have to discover a substantial surprise beyond our current understanding.

- Essentially all climate models predict equilibrium global temperature increases that are nearly linear in the logarithm of CO_2 changes. This effect is mainly due to increasing saturation of many of the infrared absorption bands of CO_2. That is, a quadrupling of CO_2 levels generally produces projected warmings that are about twice as large as those for doubled CO_2.
- Models predict that by the year 2100, global mean surface temperature changes under these two idealized scenarios would be 1.5° to 5°C.
- Sea level rise could be substantial. The projections of 50 ± 25 cm by the year 2100, caused mainly by the thermal expansion of sea water, are below the equilibrium sea level rise that would ultimately be expected. After 500 years at quadrupled CO_2 levels, the sea level rise expected due to thermal expansion alone is roughly 2 ± 1 m. Long-term melting of landlocked ice carries the potential for considerably higher values but with less certainty.
- As the climate warms, the rate of evaporation must increase, leading to an increase in global mean precipitation of about 2 ± 0.5% per 1°C of global warming.
- By 2050 or so, the higher latitudes of the Northern Hemisphere are also expected to experience temperature increases well in excess of the global average increase. In addition, substantial reductions of northern sea ice are expected. Precipitation is expected to increase significantly in higher northern latitudes. This effect mainly occurs because of the higher moisture content of the warmer air as it moves poleward, cools, and releases its moisture.

Probable Projections

The following have a greater than two out of three chance of being true:

- Model studies project eventual marked decreases in soil moisture in response to increases in summer temperatures over northern mid-latitude continents. This result remains somewhat sensitive to the details of predicted spring and summer precipitation, as well as to model assumptions about land surface processes and the offsetting effects of airborne sulfate particles in those regions.
- Climate models imply that the circum-Antarctic ocean region is substantially resistant to warming, and thus little change in sea-ice cover is predicted to occur there, at least over the next century or two.
- The projected precipitation increases at higher latitudes act to reduce the ocean's salinity and thus its density. This effect inhibits the tendency of the water to sink, thus suppressing the overturning circulation.
- Very recent research (*7*) suggests that tropical storms, once formed, might tend to become more intense in the warmer ocean, at least in circumstances where weather and geographical (for example, no landfall) conditions permit.
- Model studies project that the standard deviations of the natural temperature fluctuations of the climate system would not change significantly. This indicates an increased probability of warm weather events and a decreased probability of cold events, simply because of the higher mean temperature.

Incorrect Projections and Policy Implications

There are a number of statements in informal writings that are not supported by climate science or projections with high-quality climate models. Some of these statements may appear to be physically plausible, but the evidence for their validity is weak, and some are just wrong.

There are assertions that the number of tropical storms, hurricanes, and typhoons per year will increase. That is possible, but there appears to be no credible evidence to substantiate such assertions.

Assertions that winds in midlatitude (versus tropical) cyclones will become more intense do not appear to have credible scientific support. It is theoretically plausible that smaller-scale storms such as thunderstorms or squall lines could become stronger under locally favorable conditions, but the direct evidence remains weak.

There is a large demand for specific climate change predictions at the regional and local scales where life and life support systems are actually affected. Unfortunately, our confidence in predictions on these smaller scales will likely remain relatively low. Much greater fidelity of calculated local climate impacts will require large improvements in computational power and in the physical and biological sophistication of the models. For example, the large uncertainty in modeling the all-important responses of clouds could become even harder at regional and local levels. Major sustained efforts will be required to reduce these uncertainties substantially.

Characterizations of the state of the science of greenhouse warming are often warped in differing ways by people or groups with widely varying sociopolitical agendas and biases. This is unfortunate because such distortions grossly exaggerate the public's sense of controversy about the value of the scientific knowledge base as guidance for the policy deliberation process.

It is clear that much is known about the climate system and about how that knowledge is expressed through the use of physically based coupled models of the atmosphere, ocean, ice, and land surface systems. This knowledge makes it obvious that human-caused greenhouse warming is not a problem that can rationally be dismissed or ignored. However, the remaining uncertainties in modeling important aspects of the problem make it evident that we cannot yet produce a sharp picture of how the warmed climate will proceed, either globally or locally.

None of these recognized uncertainties can make the problem go away. It is virtually certain that human-caused greenhouse warming is going to continue to unfold, slowly but inexorably, for a long time into the future. The severity of the impacts can be modest or large, depending on how some of the remaining key uncertainties are resolved through the eventual changes in the real climate system, and on our success in reducing emissions of long-lived greenhouse gases.

References and Notes

1. The greenhouse effect for CO_2 was first calculated over 100 years ago by S. Arrhenius, *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science* **41**, 237 (1896).
2. Intergovernmental Panel on Climate Change, *Climate Change, the IPCC Scientific Assessment*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1990).
3. Intergovernmental Panel on Climate Change, *Climate Change 1995, The Science of Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1996).
4. Climate models are mathematically based models that attempt to calculate the climate, its variability, and its systematic changes on a first-principles basis. The fundamental equations solved are the conservation of mass, momentum, and energy. The interactions among the atmosphere, ocean, ice, and land surface systems are calculated on rather widely separated computational points on Earth (typical spacings are 200 to 400 km in the horizontal and 1 to 3 km in the vertical).
5. S. Manabe and R. J. Stouffer, *Nature* **364**, 215 (1993); *J. Clim.* **7**, 5 (1994).
6. The approach used here was tested and challenged in E. Barron, *Forum on Global Change Modeling, U.S. Global Change Research Program Report 95-02* (U.S. Global Change Research Program, Washington, DC, 1995). Earlier evaluations were published in J. D. Mahlman, *Climate Change and Energy Policy*, L. Rosen and R. Glasser, Eds. (American Institute of Physics, Los Alamos National Laboratory LA-UR-92-502, New York, 1992) and in J. D. Mahlman, U.S. Congressional Record, 16 November 1995, House Science Committee Hearing on Climate Models and Projections of Potential Impacts on Global Climate Change (1995).
7. T. R. Knutson, R. E. Tuleya, Y. Kurihara, in preparation.

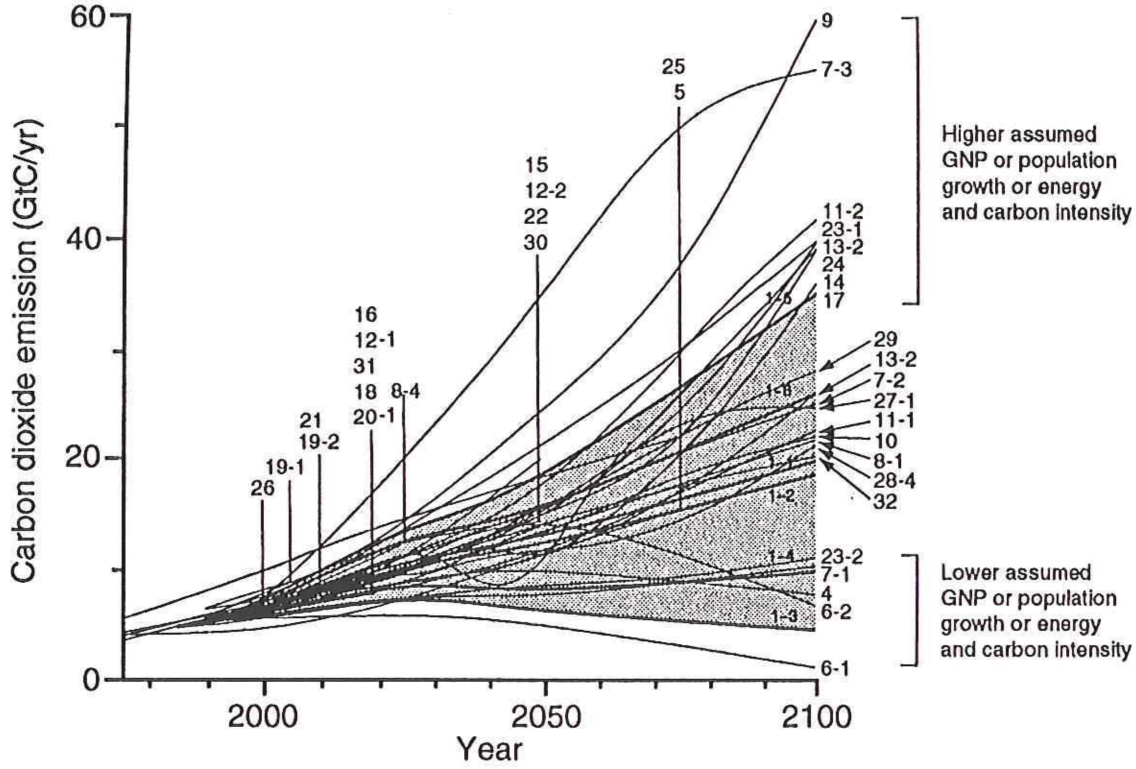

Figure 6.1: Energy-related global CO_2 emissions for various scenarios. Shaded area indicates coverage of IS92 Scenarios. Numbers correspond to list of scenarios in the Supplementary Table.

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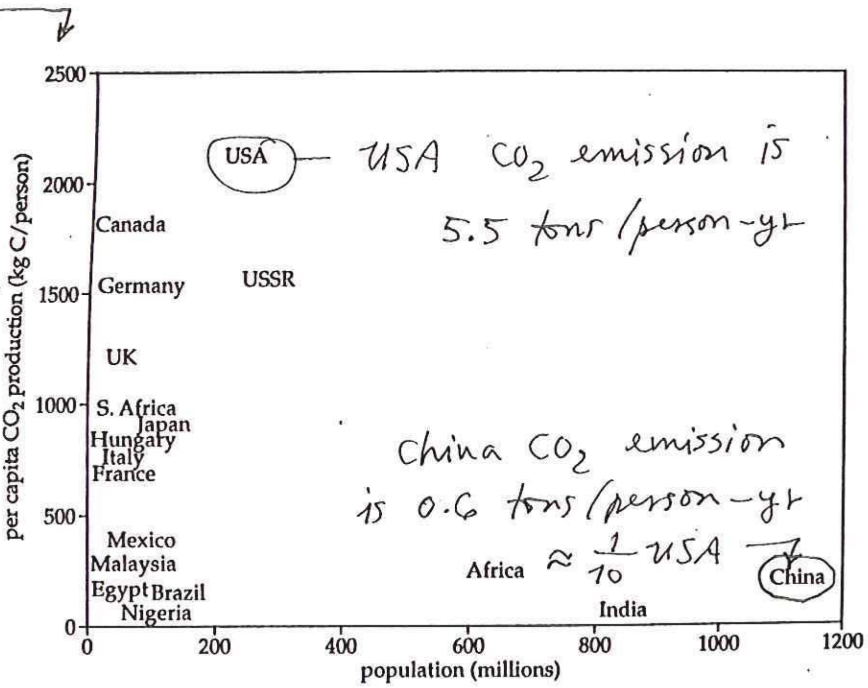
must be
wrong



USA CO_2 emission is 5.5 tons/person-yr

China CO_2 emission is 0.6 tons/person-yr $\approx \frac{1}{10}$ USA

Figure 1.4 Per capita CO_2 production from fossil fuels and cement production by country or region versus population. The industrialized countries have a high per capita output of CO_2, whereas many populous developing countries produce much less CO_2 per capita. (Data from WRI 1990.)

COMPARE AND CONTRAST

Carbon Dioxide Emissions in the United States and Europe

European emissions of carbon dioxide, the most common heat-trapping gas, are much lower than in the United States and Europe reaps a greater economic return for each pound of carbon dioxide it emits.

All figures are for 1995	Carbon dioxide emissions *Millions of tons*	Carbon dioxide emissions per capita	Carbon dioxide emissions for each dollar of gross domestic product
United States	5,229	18.0 metric tons	1.9 pounds
Europe	3,419	7.1	1.1
Germany	884	9.8	1.4
France	362	5.7	0.7
Italy	424	6.7	0.9
Britain	565	8.7	1.3

Source: International Energy Agency.

The New York Times

$$kg\,C = \frac{12}{12+16+16} \times kg\,CO_2$$

Per capita CO_2 emissions in US are more than twice European level

20 tons C / person – yr

= 1.5 GtC/yr total

= 27% of world emissions

CORRECTION

Carbon Dioxide Emissions

A chart on Thursday with an article about European efforts to reduce emissions of heat-trapping "greenhouse" gases showed erroneous figures for per capita emissions of carbon dioxide in the United States and Europe in 1995. Here are the correct figures, in metric tons.

United States	19.9
Europe	7.9
Germany	10.8
France	6.2
Italy	7.4
Britain	9.6

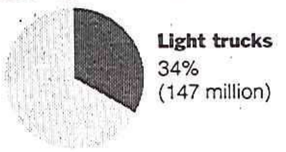
Source: International Energy Agency

On Trucks, Global Heater Included

Light trucks – which include sport utility vehicles, pickups and mini-vans – are the fastest-growing source of emissions of global warming gases in the United States. Their increasing popularity will make it harder for the United States to fulfill President Clinton's proposal to reduce American emissions to 1990 levels within 15 years.

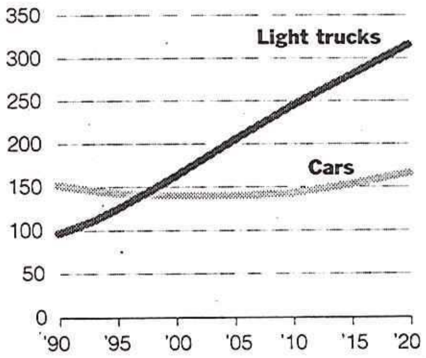
Light trucks are expected to account for 34 percent of the increase in total energy-related carbon emissions from 1990 to 2010. That total will be 32 percent higher than the 1990 level.

Total increase: 435 million metric tons



Assumes miles driven each year rises slightly slower than the current rate; the number of trucks and cars sold will be equal after 2001.

Amount of carbon emissions, projected to year 2020, in million metric tons.



Source: John German, Environmental Protection Agency researcher

The New York Times

why ?

One reason is the infatuation of US drivers with the SUV

Light truck emissions growing at 7% / yr

Sliced Another Way: Per Capita Emissions

European leaders and private environmental groups have long pointed to the United States as the largest single source of carbon dioxide emissions, which most scientists link to a global warming trend. President Bush last week pointed out that although the United States is the world's biggest emitter, it also provides the most goods and services to global markets.

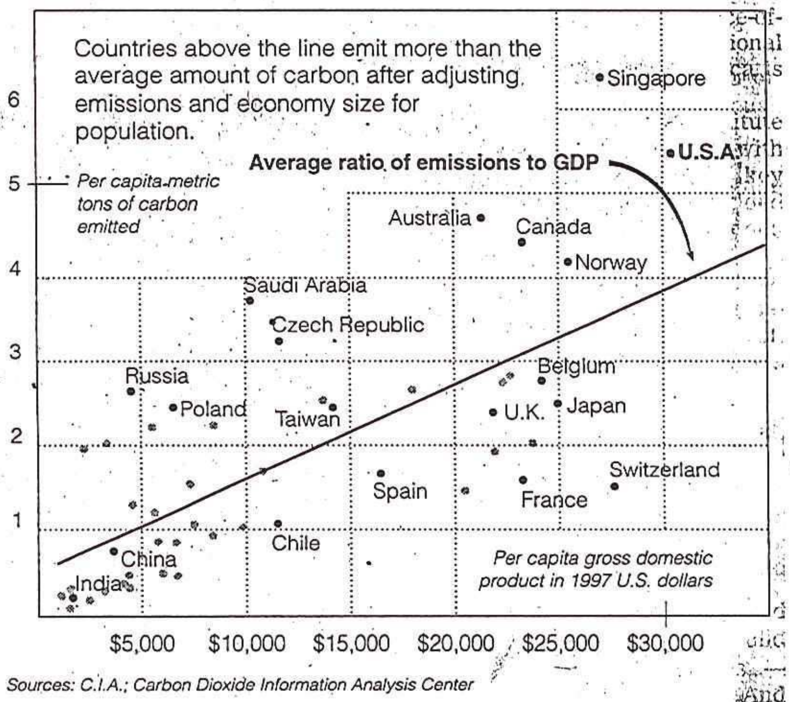
But when G.D.P. and emissions are measured and compared on a per capita basis, the playing field suddenly gets much more mixed, with Singapore, Australia, and Saudi Arabia joining the United States in the group with far above average output of carbon dioxide, while other counties prove more efficient at producing things without adding to the greenhouse effect.

The conclusion some economists draw is that prosperity does not always have to come with environmental costs, and environmental cleanups can be achieved without necessarily harming economies.

ANDREW C. REVKIN

Pollution vs. Prosperity

Among selected countries



Countries above the line emit more than the average amount of carbon after adjusting emissions and economy size for population.

Sources: C.I.A.; Carbon Dioxide Information Analysis Center

James Bronzan/The New York Times

BY THE NUMBERS

Carbon Emissions

The U.S. emitted more carbon dioxide per capita than European countries in 1997.

Metric tons of carbon per capita

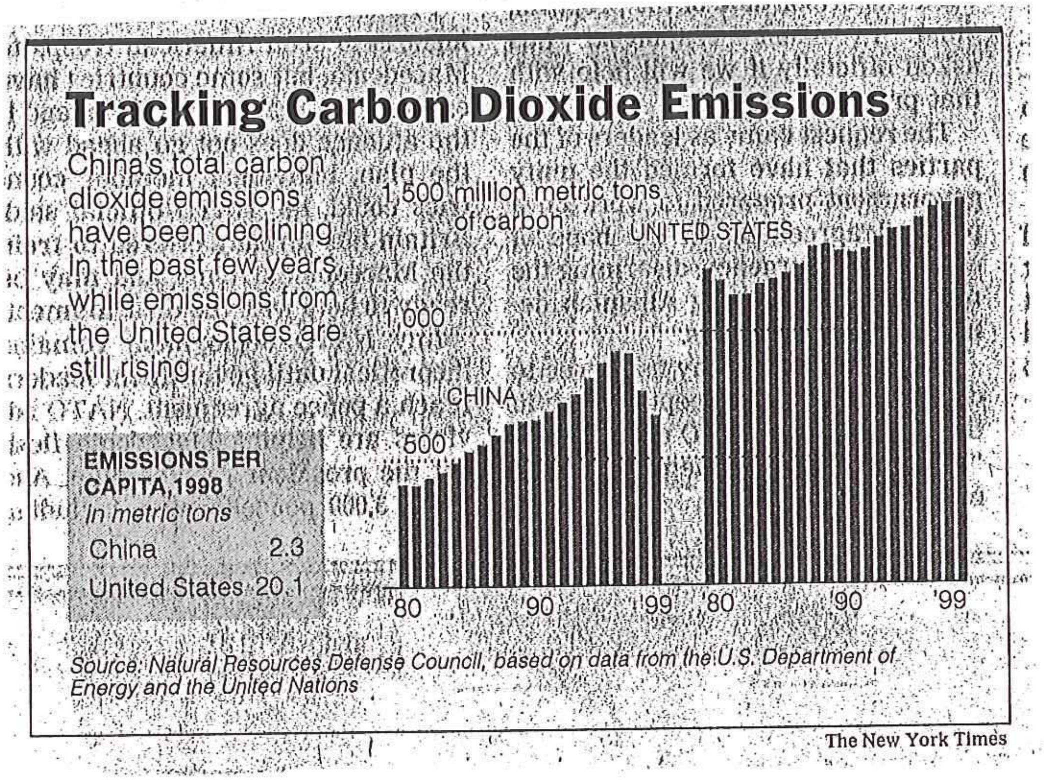
Source: Carbon Dioxide Information Analysis Center

The New York Times

Table 1.2 Estimates of carbon released by country in millions of tonnes

From industrial sources (1982)*		From land use changes (1989)†	
USA	1135	Brazil	454
USSR	901	Indonesia	124
China	413	Burma	83
Japan	226	Mexico	64
W. Germany	181	Thailand	62
UK	141	Colombia	59
Poland	112	Nigeria	57
France	111	Zaire	57
India	78	Malaysia	50
Italy	88	India	41

* Data from UNEP (1991)
† Data from Leggett (1990)



Tracking Carbon Dioxide Emissions

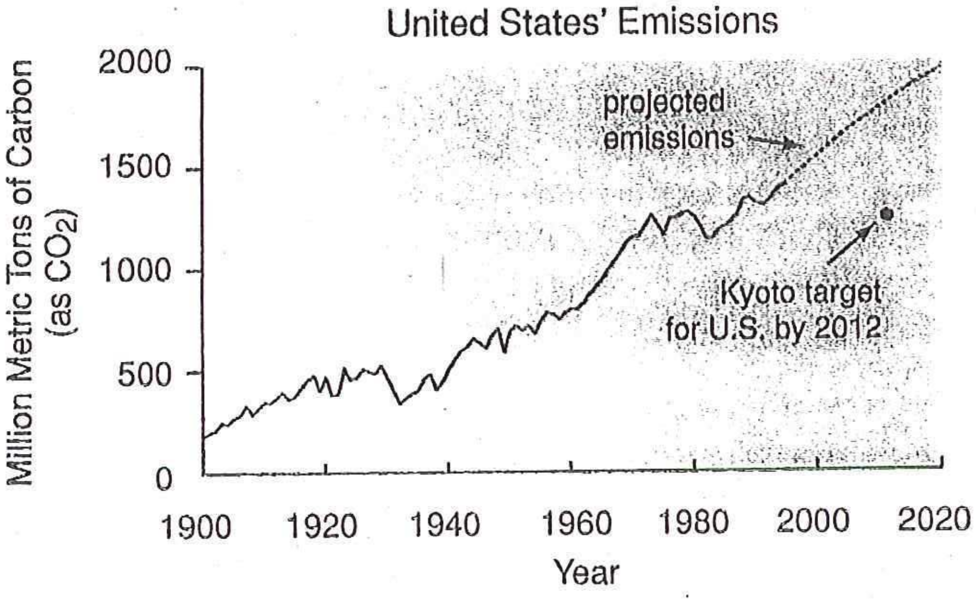
China's total carbon dioxide emissions have been declining in the past few years, while emissions from the United States are still rising.

EMISSIONS PER CAPITA, 1998
In metric tons

China	2.3
United States	20.1

Source: Natural Resources Defense Council, based on data from the U.S. Department of Energy and the United Nations

The New York Times

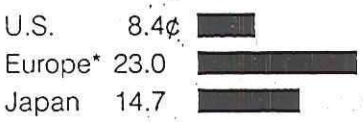


Different Places, Different Paces

Energy costs in the United States are much lower than in Europe or Japan, which helps explain why Americans consume far more energy per person than the Japanese or Europeans. Even though the United States has made greater gains in efficiency, improvement has slowed in the 1990's and its economy uses energy much more inefficiently than other industrial nations.

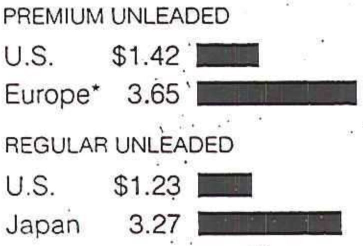
Cost of electricity for households

U.S. cents per kilowatt-hour in 1996



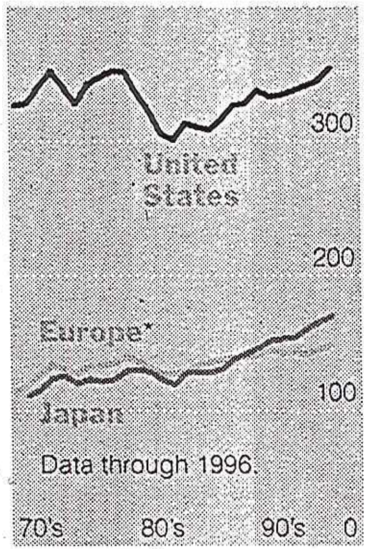
Cost of gasoline

U.S. dollars per gallon in 1997



Energy use per person

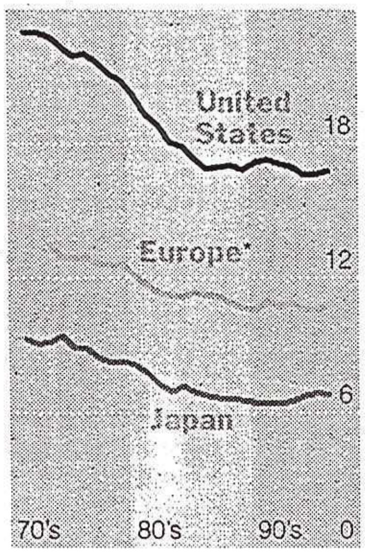
Millions of B.T.U.'s



Data through 1996.

Energy use per dollar of G.D.P.

Thousands of B.T.U.'s per 1997 dollar



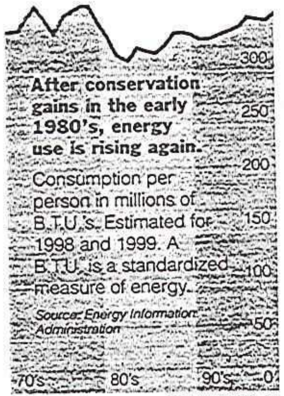
*Does not include Czech Republic, Hungary and Poland because complete data were not available.

Source: Energy Information Administration

The New York Times

U.S. Splurging on Energy After Falling Off Its Diet

By ALLEN R. MYERSON



After conservation gains in the early 1980's, energy use is rising again.

Consumption per person in millions of B.T.U.'s. Estimated for 1998 and 1999. A B.T.U. is a standardized measure of energy.

Source: Energy Information Administration

The New York Times

POWER HUNGRY

A special report.

ARVADA, Colo. — Twenty-five years after an oil embargo proved that fuel supplies were neither reliable nor endlessly cheap, the United States has given up almost all the gains it made in conserving energy. On average, Americans have returned to consuming nearly as much energy as ever before.

From 1973, when Arab oil producers choked off their shipments to the United States, through 1983, the nation reduced its energy consumption even as the population and economy expanded. Prodded by higher costs and led on conservation crusades by Presidents Richard M. Nixon, Gerald R. Ford and Jimmy Carter, Americans learned to do more with less.

That effort is still yielding great benefits. Owners of older buildings and homes installed thicker insulation and tighter windows. As technology improved, every new home, factory and car came with far more efficient appliances, machines and engines than in the 1970's. But energy demand has risen so much since the mid-1980's that, next year, the Energy Department predicts, consumption per person will come to within 2 percent of the peak in 1973, before any of these energy-saving advances had begun.

Declining energy prices — now lower in real terms than before the first embargo — have made the difference. In the dollar-a-gallon era, why spend much time or money saving a gallon or a watt?

Evidence of the more energy-intensive life style is everywhere. Since the early 1970's, as the average household has shrunk by a sixth, the average new home has grown by a third. Even moderately priced homes are now stuffed with energy-hungry features, from central air-conditioning to Jacuzzis and security systems.

Look at families like T. C. and Michael McCracken and their year-old daughter, Lydia. The McCrackens, avid hikers, are far more willing than most Americans to shop for energy-saving appliances or ride the bus to work. But here in Arvada, outside Denver, standard features of their nearly completed tract home include ceilings so high that overhead fans, finding a new season and purpose, are required in winter to blow rising heat back down. With 2,600 square feet to fill, Mr. McCracken plans to install a home office, a home theater and a home brewery fed by its own gas line. What Mrs. McCracken calls a "killer kitchen" has all the standard appliances and the electrical capacity for more than a dozen others, plus room to seat a family of 10.

Energy use is rising even faster on the roads. Next year, Americans are expected to burn more fuel per person than in 1973, be-

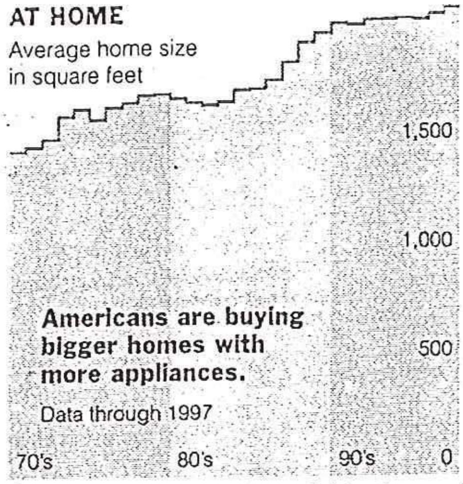
Continued on Page C6

Living Larger

In the 1990's, environmentalism has been a favored cause. But Americans are using almost as much energy as ever before. Homes are larger, requiring more energy to heat, cool and run more appliances. On the road, fuel consumption is rising even faster. Industry is also using more energy, but thanks to big efficiency gains in the 1980's, it is still consuming less than two decades ago after adjusting for growth in output.

AT HOME

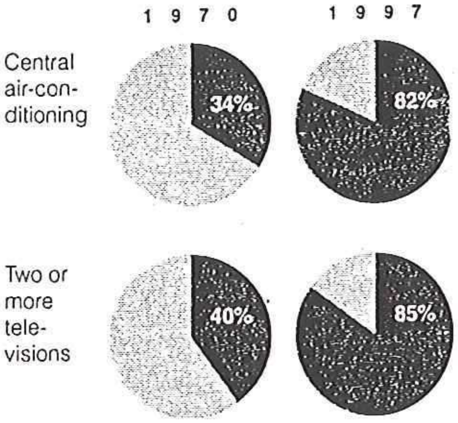
Average home size in square feet



Americans are buying bigger homes with more appliances.

Data through 1997

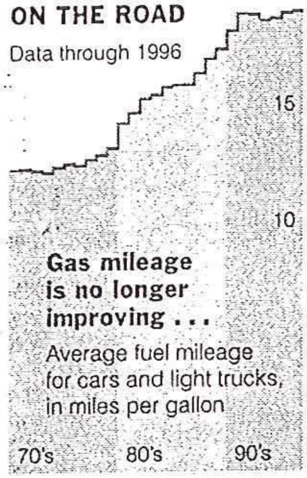
Percentage of homes with ...



Sources: National Association of Home Builders; Consumer Electronics Manufacturers Association

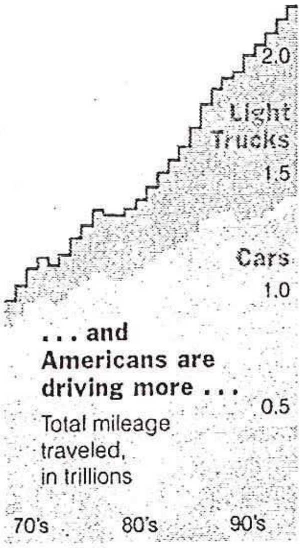
ON THE ROAD

Data through 1996



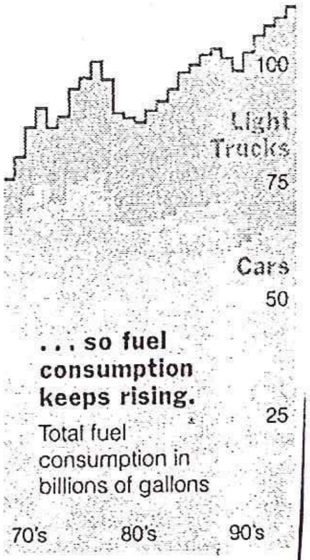
Gas mileage is no longer improving . . .

Average fuel mileage for cars and light trucks, in miles per gallon



. . . and Americans are driving more . . .

Total mileage traveled, in trillions



. . . so fuel consumption keeps rising.

Total fuel consumption in billions of gallons

Sources: Oak Ridge National Laboratory; Federal Highway Administration

AT WORK

Industrial energy use has risen . . .

Energy use by industry in quadrillion B.T.U.'s

. . . as the cost has dropped . . .

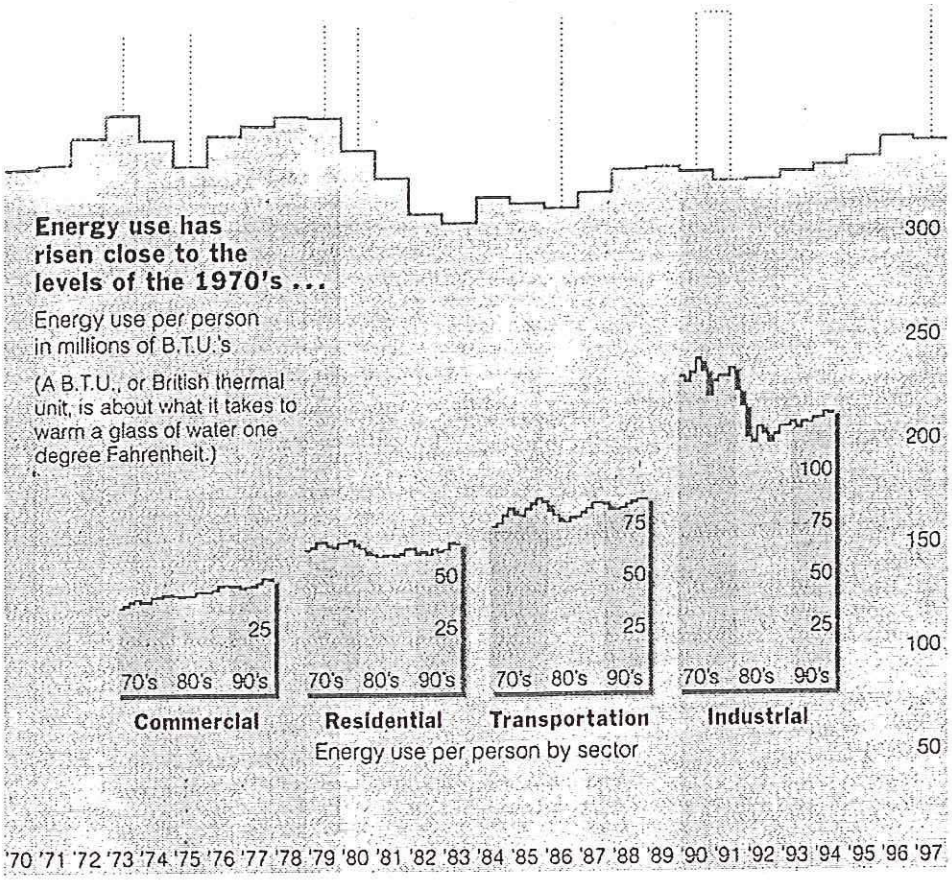
Price of electricity sold to industry in cents per kilowatt-hour (in 1992 dollars)

. . . but manufacturers use energy more productively than before.

Energy use by industry (in B.T.U.'s) per thousand dollars of manufacturing sales (1992 dollars)

Sources: Cambridge Energy Research Associates, Energy Information Administration

The New York Times

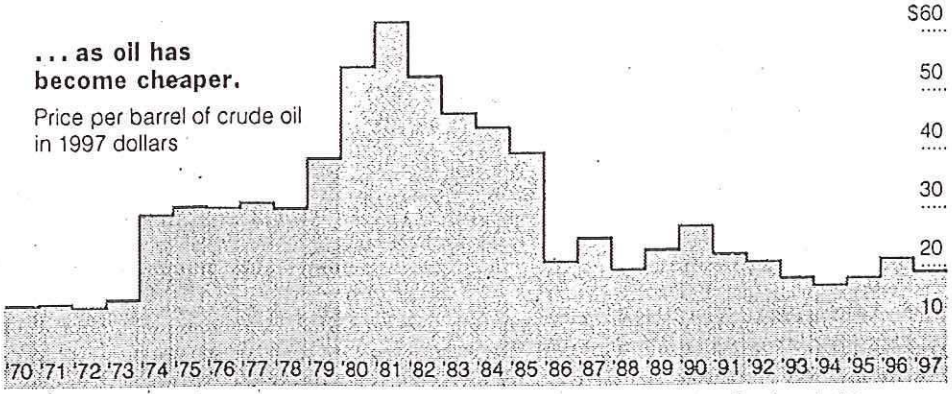


Energy use has risen close to the levels of the 1970's ...

Energy use per person in millions of B.T.U.'s

(A B.T.U., or British thermal unit, is about what it takes to warm a glass of water one degree Fahrenheit.)

Energy use per person by sector

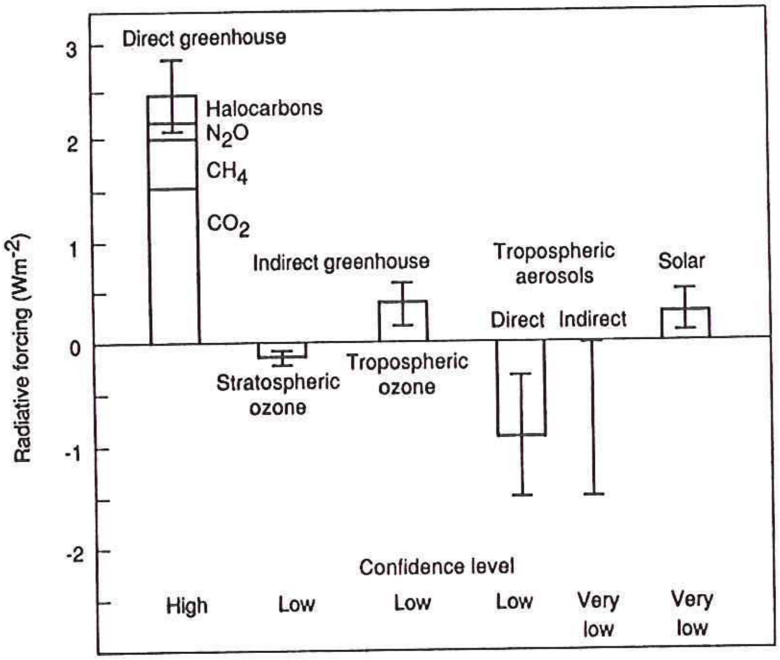


... as oil has become cheaper.

Price per barrel of crude oil in 1997 dollars

Sources: Cambridge Energy Research Associates; Energy Information Administration; American Petroleum Institute

The New York Times



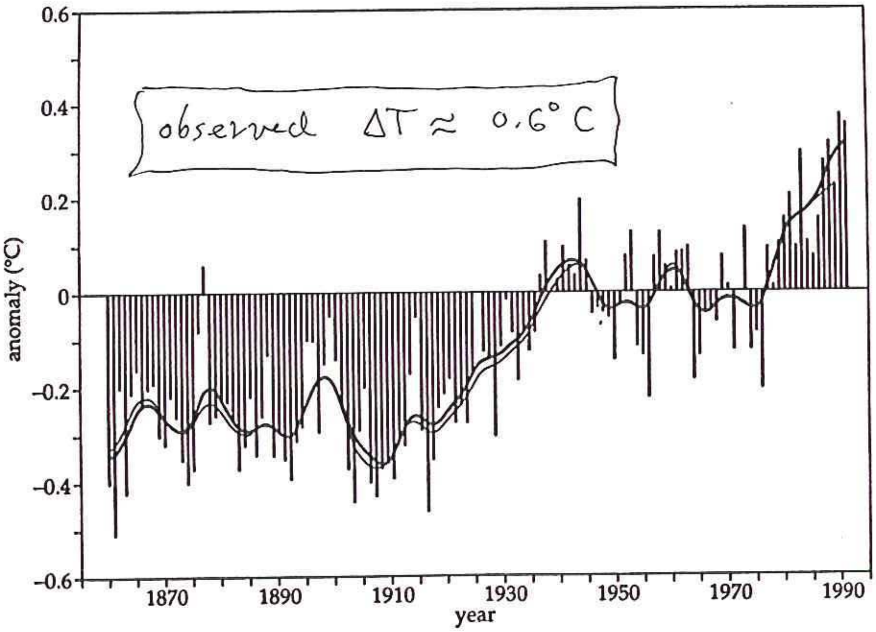
Total anthropogenic radiative forcing

$$\delta u_0 = 2 \text{ W/m}^2 \quad (u_0 = 388 \text{ W/m}^2)$$

Purely radiative temperature increase

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

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



$\boxed{\text{observed } \Delta T \approx 0.6^\circ \text{C}}$

But there is considerable natural variability.