Global Warming

Humans are taking organic C, long buried within the ⊕, pumping it out as petroleum or mining it as coal, burning it & releasing CO_2 to the atmosphere.

This has happened significantly only in past ~ 100 years — the industrial revolution

Current rate of CO_2 production due to fossil fuel consumption is

5.5 Gt/yr

This includes a small fraction due to cement production

$$\underset{CaCO_3}{\text{limestone}} \xrightarrow[\text{heat}]{} \underset{\uparrow\ \text{lime or cement}}{CaO} + \overset{\text{to atmosphere}}{CO_2}$$

$$CaO + H_2O \to Ca(OH)_2$$

concrete (e.g. floor of Room 10)

Fig. 11.18 (Holland & Petersen) history of CO_2 release by humans past 130–140 yrs (since industrial revolution.

For comparison recall that natural CO_2 cycle involves ~ 65 GtC/yr fixation by photosynthesis & respiration by bacteria, etc.

Human fossil fuel consumption ~ 10% perturbation.

first was Svante Arrhenius

~~First person~~ one of first people to think about environmental consequences of this — Roger Revelle — then at UCSD

1958 — suggested to Charles Keeling to try to measure — established observatory at Mauna Loa, Hawaii — high above vegetation ⇒ average CO_2 ~ unaffected by photosynthesis.

Continuous record since that time — possibly most famous time series in geosciences.

Annual fluctuations ± 3 ppm due to seasonal cycle of photosynthesis

Superimposed on long-term increase from 316 ppm in 1958 to 360 ppm in 1990 — average 1.2 ppm/yr.

Clear evidence of increase in accumulation rate

1.5 ppm/yr or 0.4% currently

$$\frac{1.5}{360} = 0.4\%$$

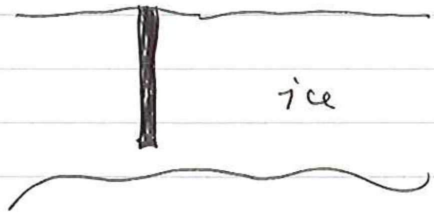
This famous record has led to intensive study of this phenomenon during the past decade.

Other observatories (e.g. SPA) established.

CO_2 increase found to be a global phenomenon.

Extension of record into the past.

Drilling of ice cores in Greenland & Antarctica



Known ice accumulation rate gives chronology (cm/yr).

Measure % CO_2 in trapped air bubbles in ice.

Melt ice — collect trapped air — measure % CO_2

Pre-industrial level ~ 280 ppm

Keeling Mauna Loa measurements began 1958 — already 315 ppm

Clear evidence of exponential growth.

What is current growth rate in GtC/yr?

(0.0042)(760 GtC in atmosphere)

$$\boxed{= 3.2\ \text{GtC/yr}}$$

↑ observed rate of increase

Increase in growth rate from ~1 ppm/yr to ~1.5 ppm/yr in past 40 yrs.

We also know very well the rate at which we are adding CO_2 to the atmosphere by fossil fuel burning and — to a much lesser extent — cement production

$$\boxed{5.5\ \text{GtC/yr}}$$

← emission rate

This discrepancy has come to be known as the <u>missing carbon problem</u>

Fossil fuel consumption is releasing ~50% more CO_2 to atmosphere than we see — why?

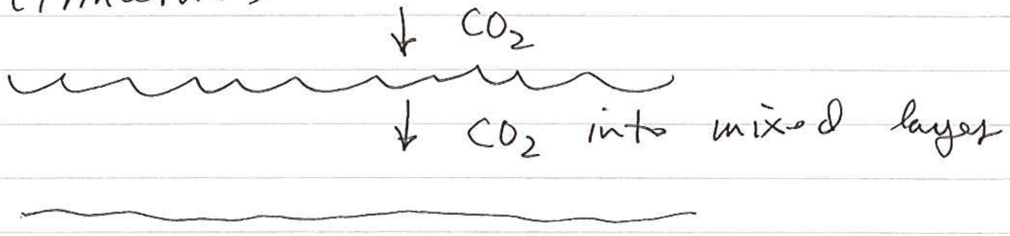
Our current understanding of the <u>global</u> carbon budget is as follows:

fossil fuels & cement	5.5 GtC/yr
tropical deforestation	1.6 GtC/yr
Total anthropogenic emissions	7.1 GtC/yr

Discrepancy even larger!

Two sinks have been determined with greater certainty by recent work:

(1) uptake by oceans — Jorge Sarmiento (Princeton)



phytoplankton $CO_2 + H_2O \rightarrow CH_2O + O_2$

↓ die & sink (biological pump)

↓ slow transport into deep oceans ~ 1000 yr timescale (thermohaline circulation)

also sinking of cold CO2 rich water

Ocean uptake cannot be measured. Must be modelled. Best estimate

$$\boxed{\text{2.0 GtC/yr into oceans}}$$

example — no virgin forest in Princeton area but lots of 2^{d} growth

people used to burn wood for fuel & be much more reliant upon local agriculture

Finally, just in past 2–3 years:

Northern hemisphere forest regrowth
e.g. Princeton — my backyard

0.5 GtC/yr

Net effect of land-use changes: 1.6 − 0.5
= 1.1 GtC/yr

Net imbalance 1.4 ± 1.5 GtC/yr

Maybe zero within errors.

Many ~~[illegible]~~ suggestions:

(1) CO_2 fertilization — plants need CO_2 — increased concentration in atmosphere has stimulated growth

(3) northern forest regrowth may still be underestimated

How much would we need?

$$\underset{\uparrow \text{NPP}}{\frac{1.4}{65}} = 2\%$$

(2) nitrogen fertilization — excess nitrate from farmer's fields has fertilized phytoplankton production

Five years ago, missing C problem thought to be 'very important' — now:

- new sink found
- no dearth of explanations for remaining discrepancy
- 1.4 ± 1.5 — big deal anyway.

The anthropogenic increase in atmospheric CO_2 from 280 ppm to 360 ppm today has increased the "thickness" of the greenhouse "glass" slightly.

How much? Enough to increase the re-radiated IR by 1.6 W/m^2 (see Fig. 3

Other activities have also affected the radiative forcing

sources of methane: rice paddies, bovine flatulence natural gas leakage

Methane & other greenhouse gases

Halocarbons — refrigerants (CFC) more notorious for their role in destroying polar stratospheric ozone

Also human release of aerosols — cause increased scattering ⇒ slight increase in albedo by ~ 0.3%

$$-(.003)(340\ W/m^2) \simeq -1\ W/m^2$$

Total anthropogenic effect ~ 2 W/m^2 increase with large error bars

Sarmiento et al. (1998) study

Inverted ~ 60 atmospheric CO_2 trends for 3 uptake sources.

Need to model inputs (well known), ocean uptake, redistribution by mean winds, forest cover, ...

Find NA uptake 1.7 GtC/yr

In conflict with US Forest Service inventories — only 0.2 – 0.3 GtC/yr.

Controversial — US emissions are 1.6 GtC/yr — would ⇒ US is break-even — no need for emission controls.

Strong tradeoff with NA – Eurasian takeup.
Reason: result relies on weak EW trends (which are smoothed by zonal winds)

but there is not

Map shows theoretical anomaly in absence of takeup — should be an excess of atmospheric CO_2 over NA because of emissions

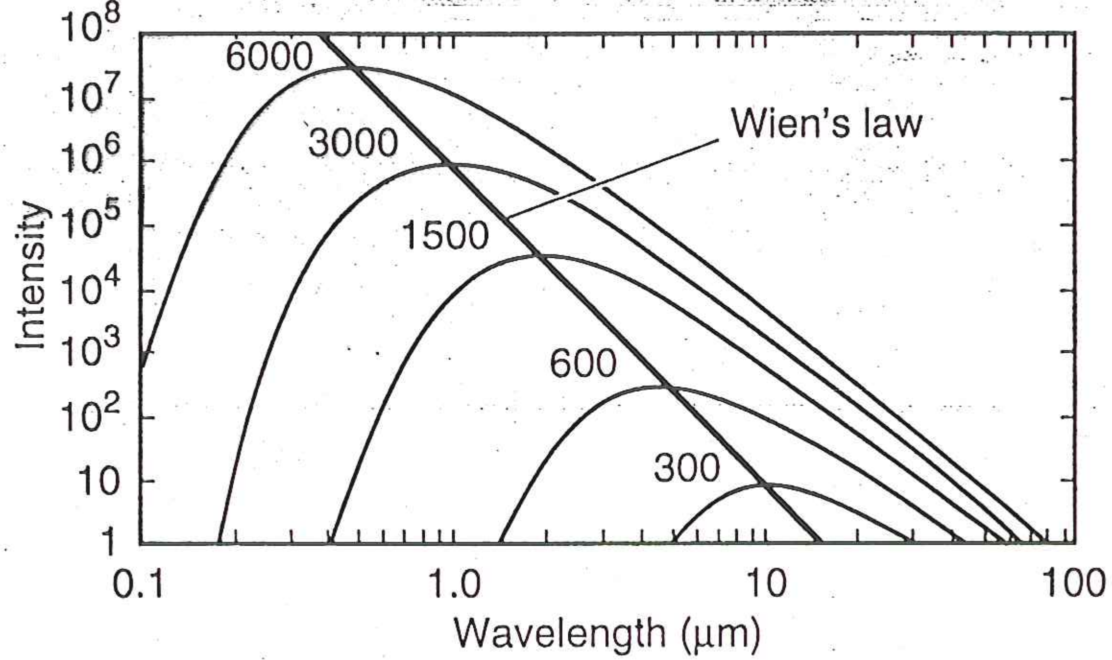
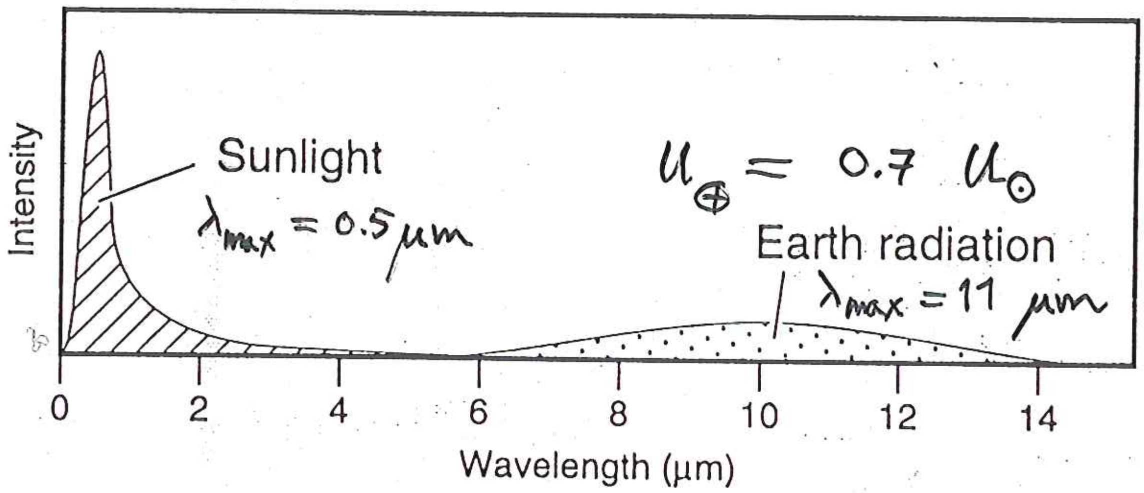


Figure 3.7 Blackbody radiation spectra as a function of temperature (kelvin), over the entire range of temperatures relevant to environmental studies. The values are displayed here on a log-log graph, so that both the wavelength and intensity scales are greatly compressed and cover many orders of magnitude.

Figure 3.8 The relative spectra of sunlight and Earth's blackbody radiation (referred to as terrestrial radiation or Earthglow). The spectral regions of the emissions are seen to be quite distinct, with little overlap of spectra.

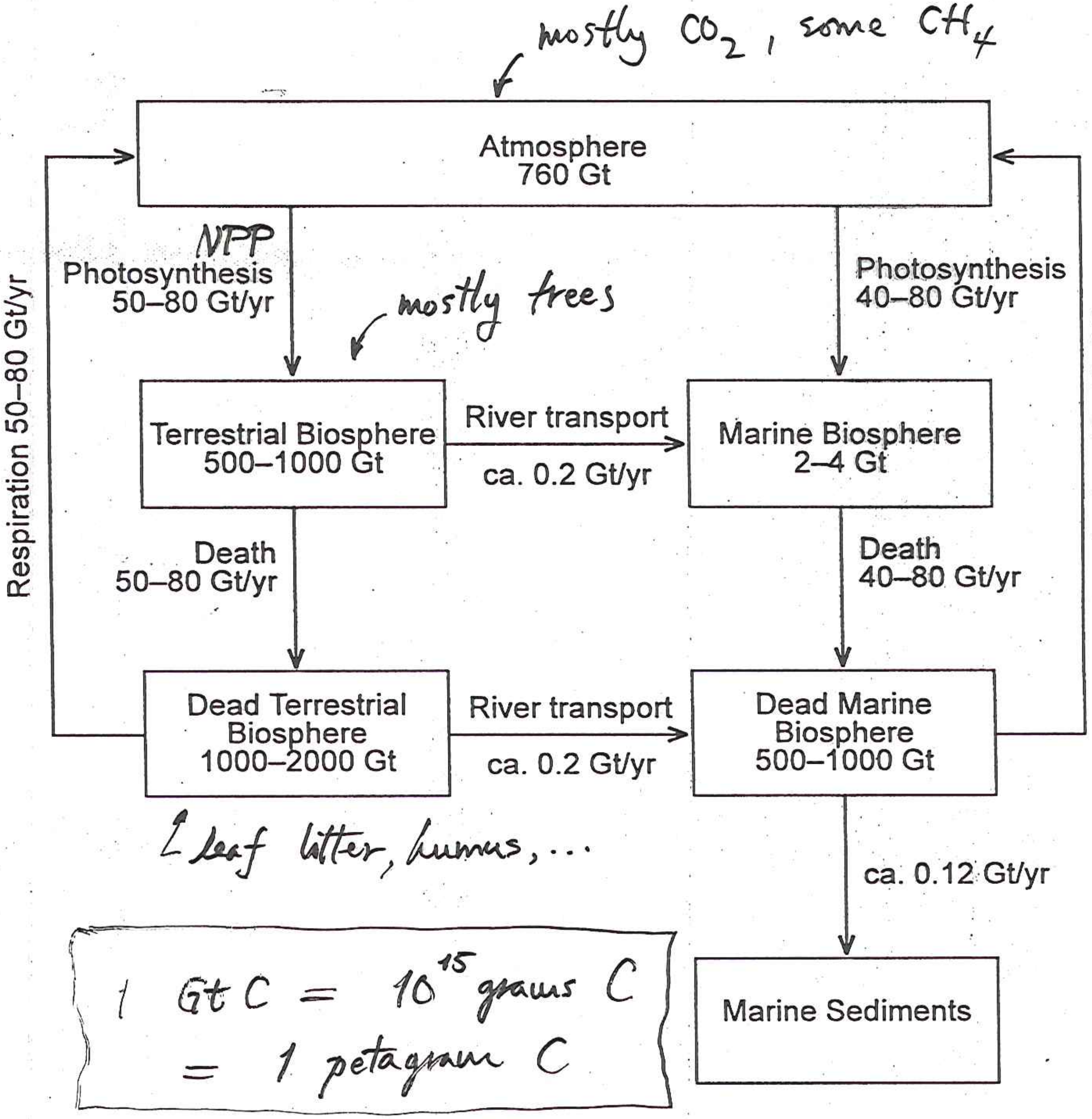


$\lambda_{max} = 0.5 \mu m$

$U_{\oplus} = 0.7 \ U_{\odot}$

$\lambda_{max} = 11 \ \mu m$

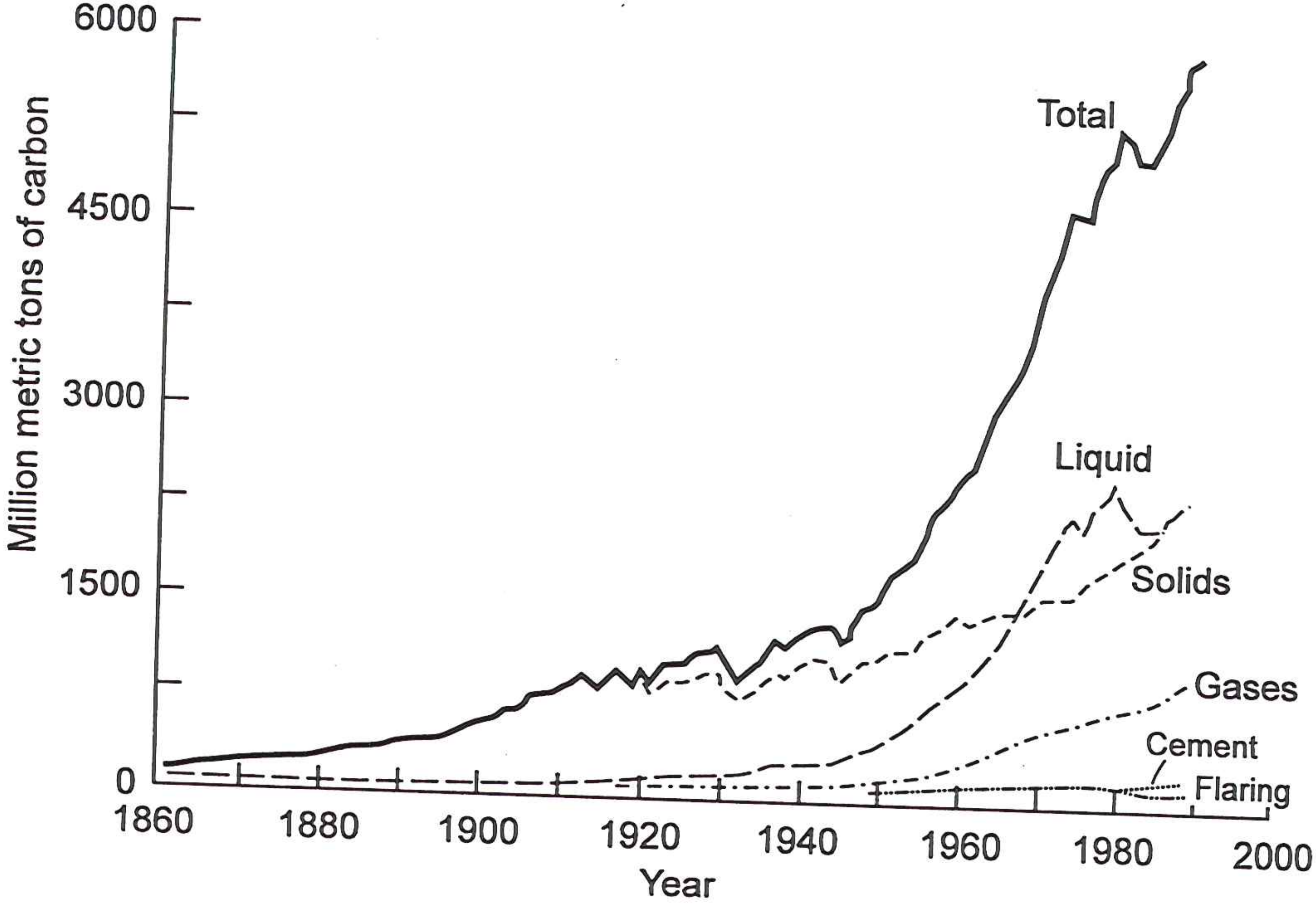
Steady-state box model for carbon



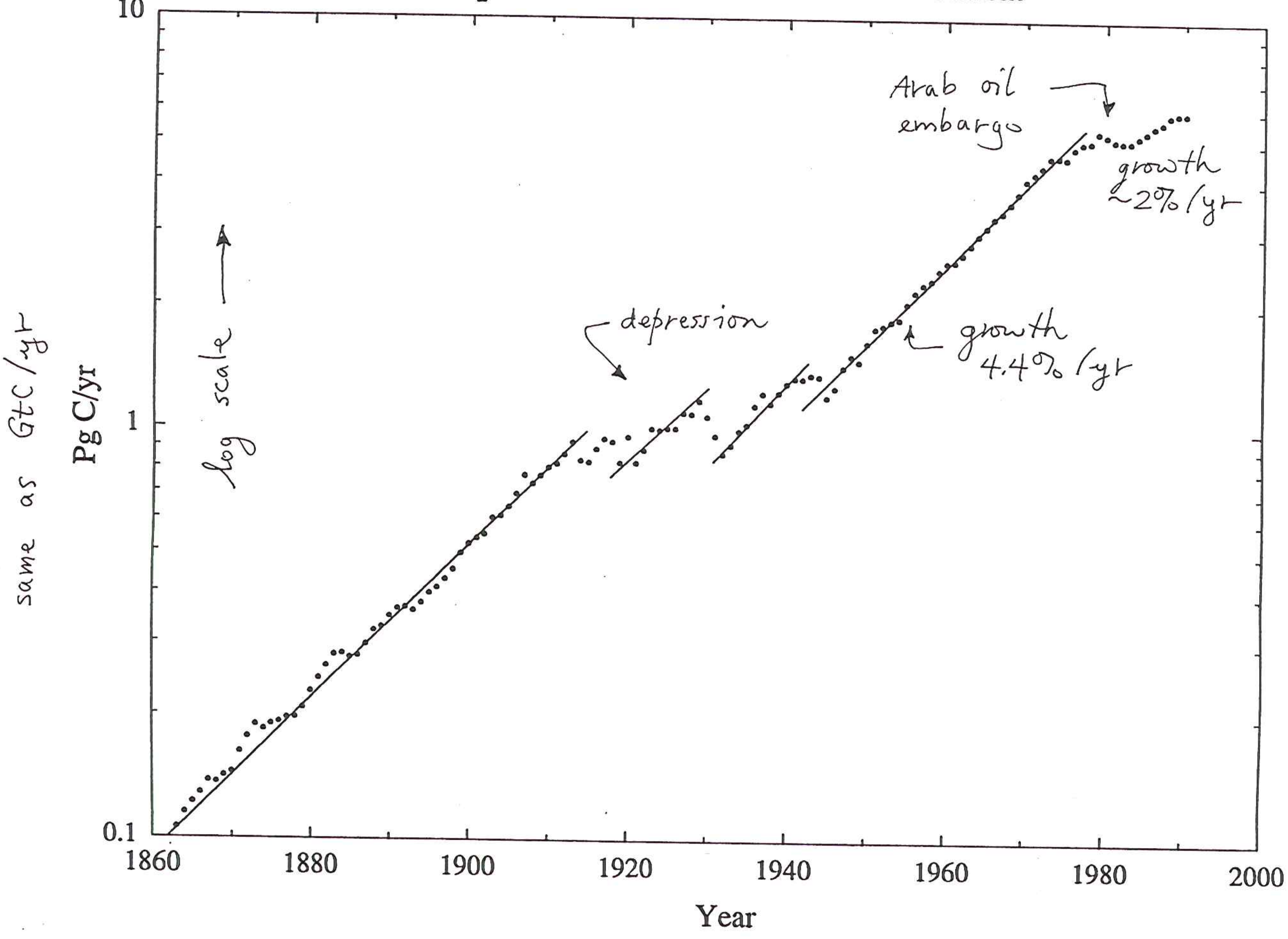
$1 \text{ Gt C} = 10^{15} \text{ grams C}$
$= 1 \text{ petagram C}$

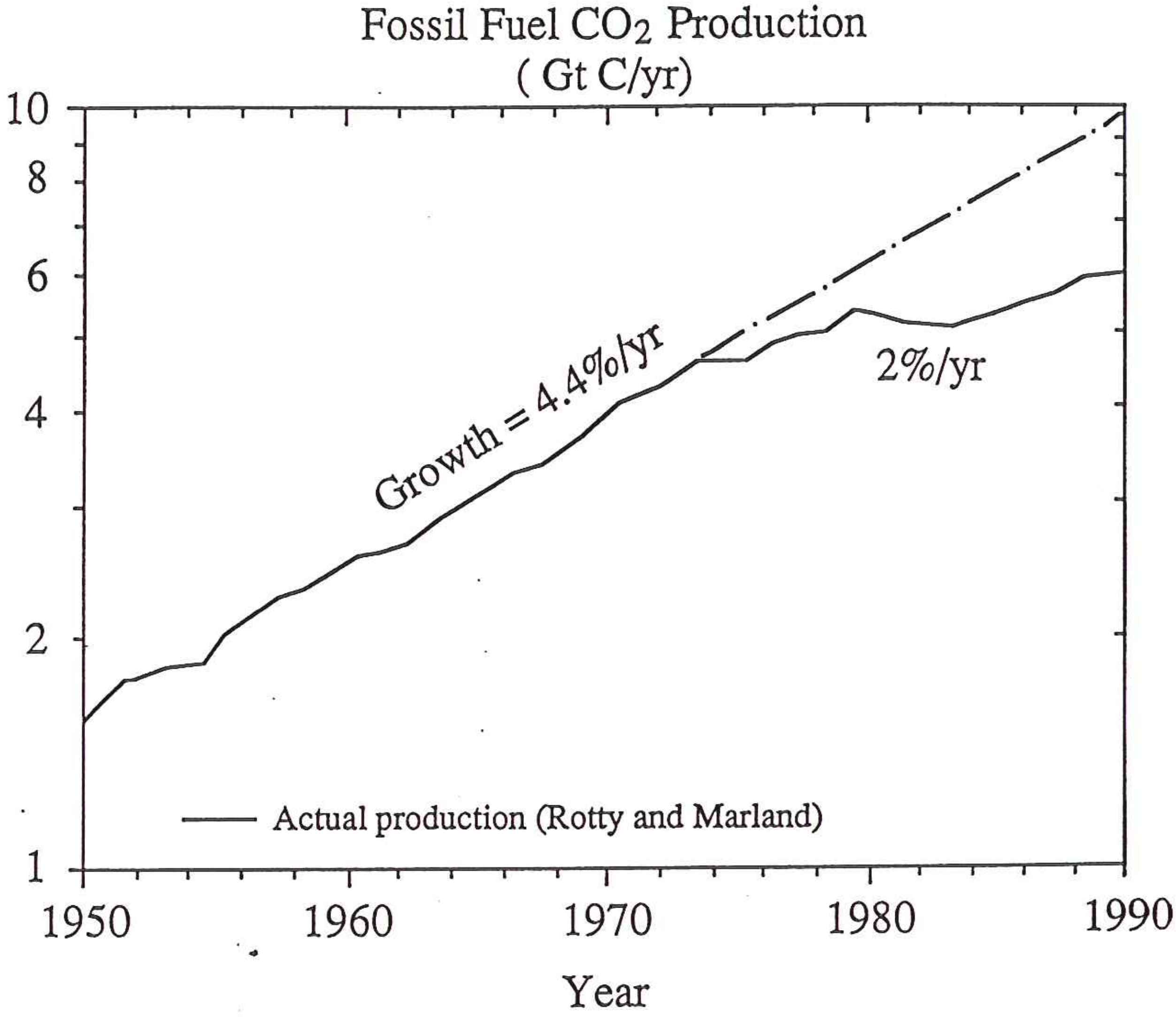
Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)

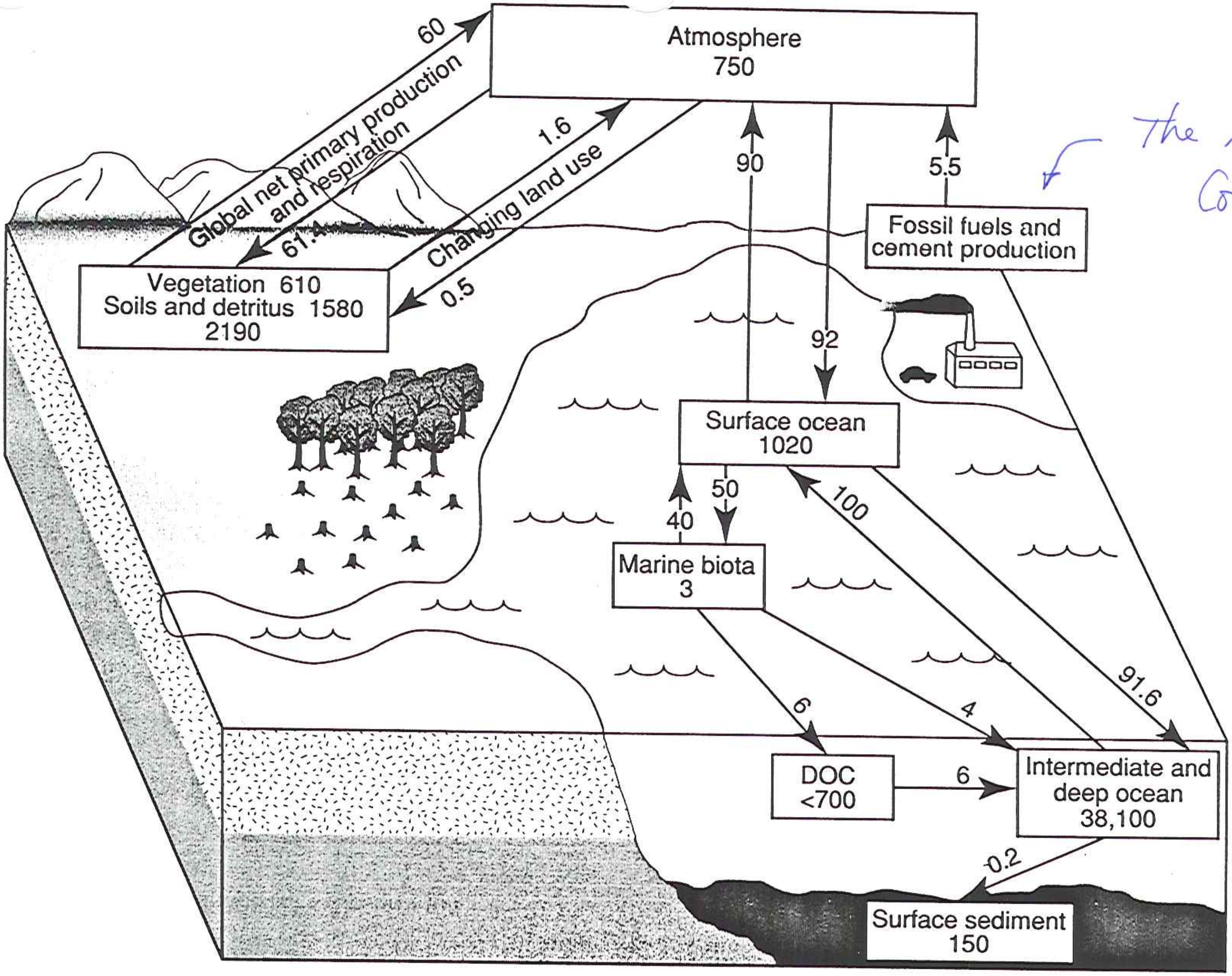
Figure 11.18. Global CO_2 emissions from fossil fuel burning and cement manufacture, 1860–1989. (From *Trends '91: A Compendium of Data on Global Change*)



CO_2 Production from Fossil Fuels and Cement

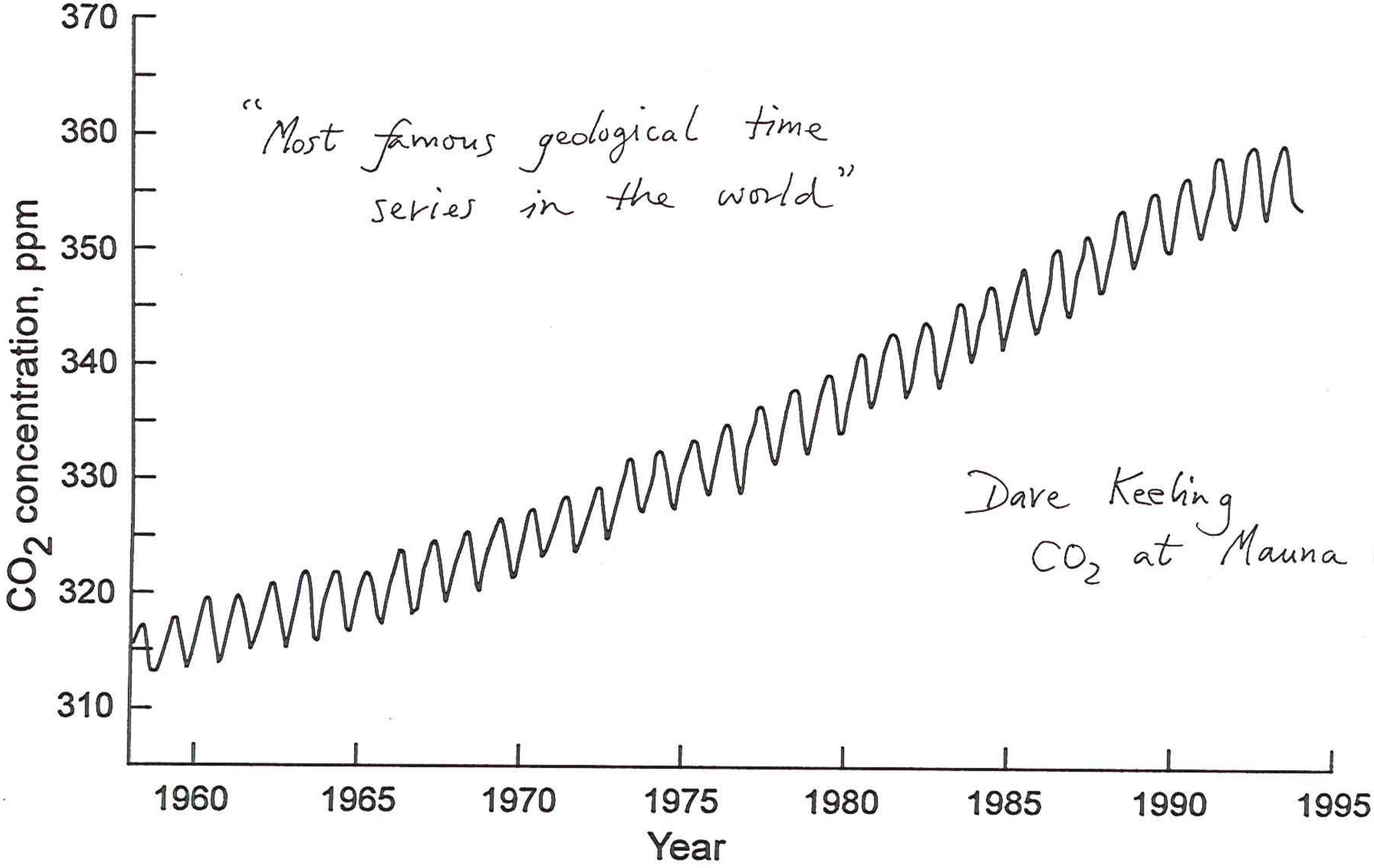



Fossil Fuel CO_2 Production
(Gt C/yr)
10
8
6
4
2
1
1950
1960
1970
1980
1990
Year
Growth = 4.4%/yr
2%/yr
Actual production (Rotty and Marland)



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

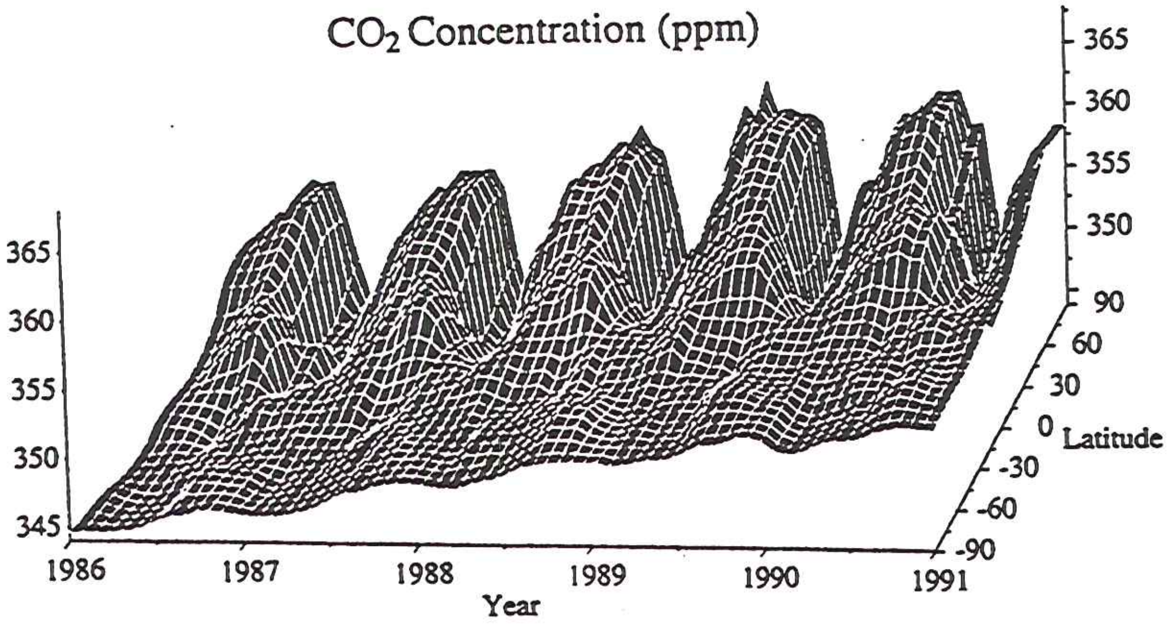


Fig. 9. Smoothed atmospheric CO_2 data as measured by the National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory's Flask Sampling Program (Conway et al. 1991).

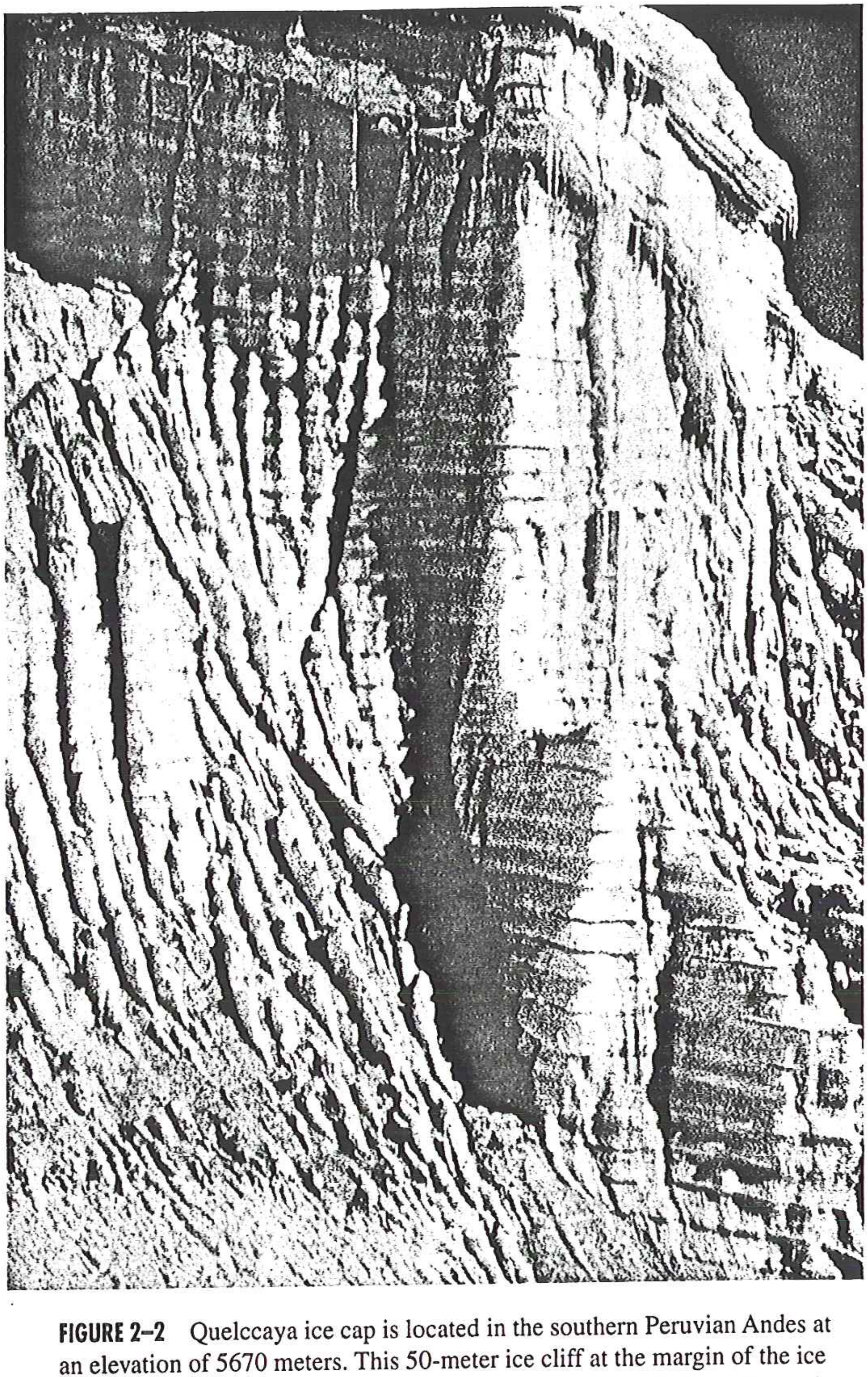
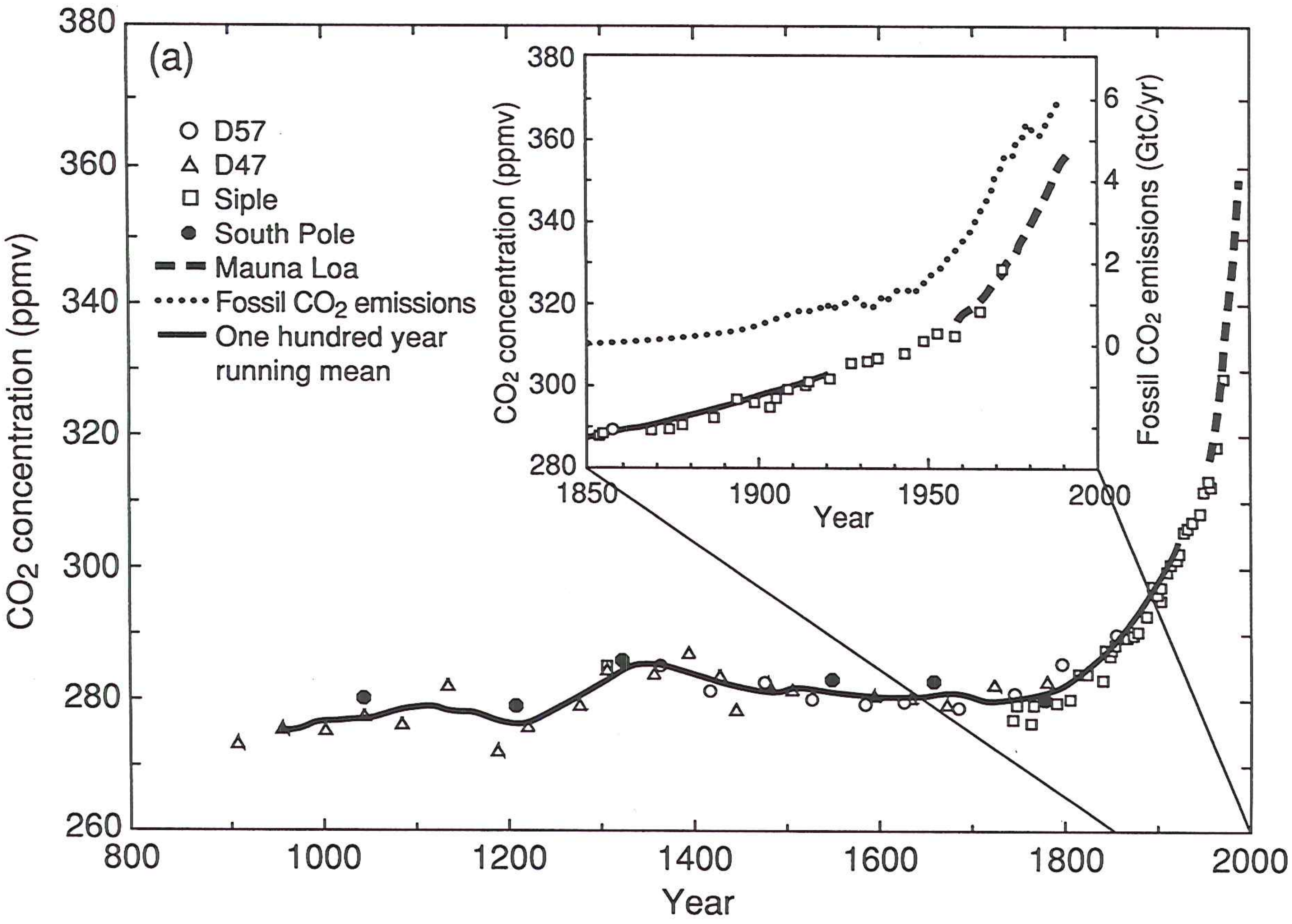
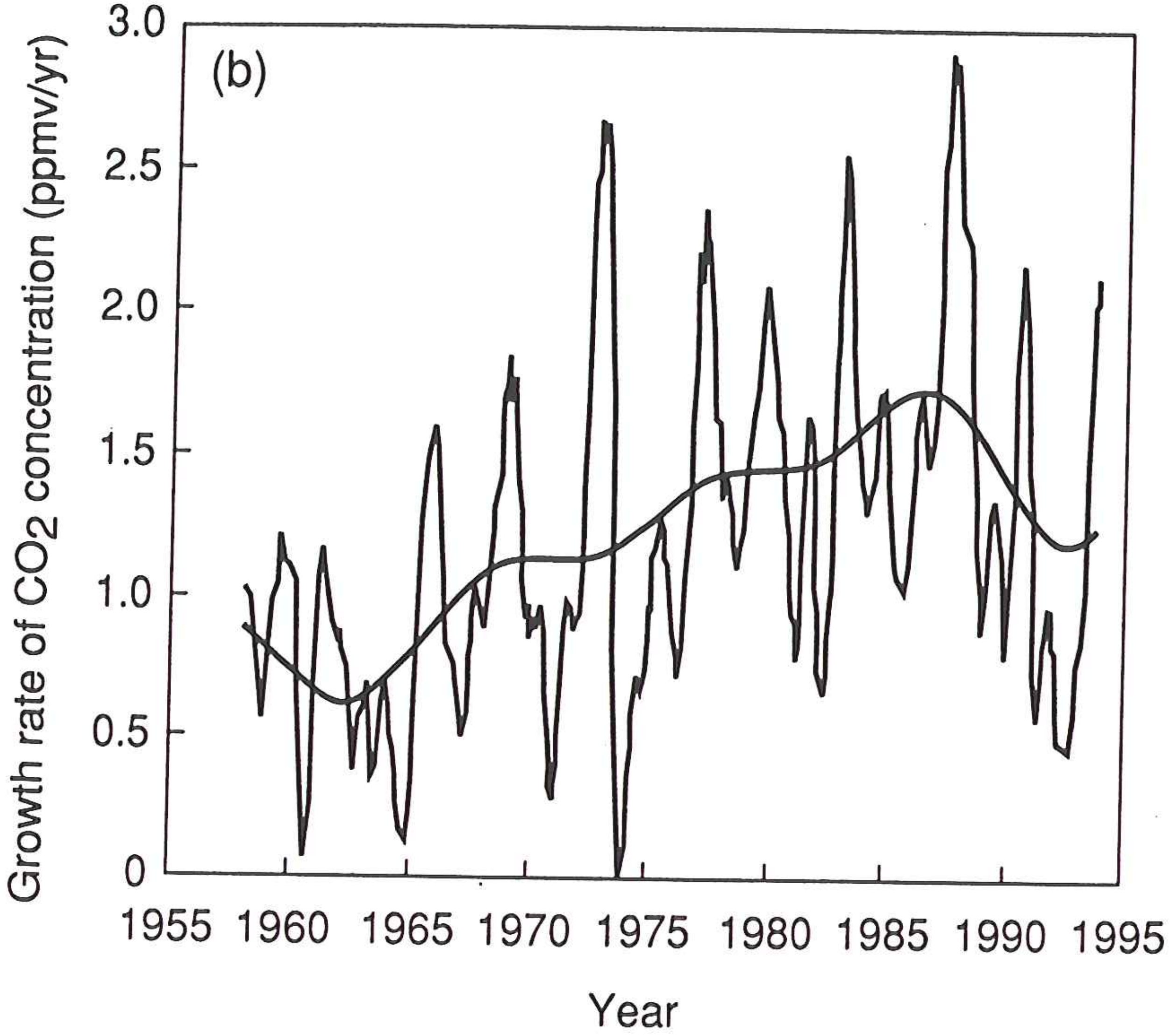


FIGURE 2–2 Quelccaya ice cap is located in the southern Peruvian Andes at an elevation of 5670 meters. This 50-meter ice cliff at the margin of the ice cap, photographed in 1983, has disappeared as of August 1995 as the result of increasing temperature (discussed in Chapter 6). This ice cap has annual layers (about 0.75 meters each) dating back 1500 years. (Photograph courtesy of Lonnie G. Thompson, Department of Geological Science and Byrd Polar Research Center of The Ohio State University.)

Figure 1.3 An ice core from the Antarctic glacier. The regions of annual surface thawing and recrystallization are clearly visible. (Courtesy of Robert Delmas, CNRS, France.)


(a)
○ D57
△ D47
□ Siple
● South Pole
Mauna Loa
Fossil CO_2 emissions
One hundred year running mean
CO_2 concentration (ppmv)
260
280
300
320
340
360
380
Year
800
1000
1200
1400
1600
1800
2000
CO_2 concentration (ppmv)
280
300
320
340
360
380
Fossil CO_2 emissions (GtC/yr)
0
2
4
6
Year
1850
1900
1950
2000



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

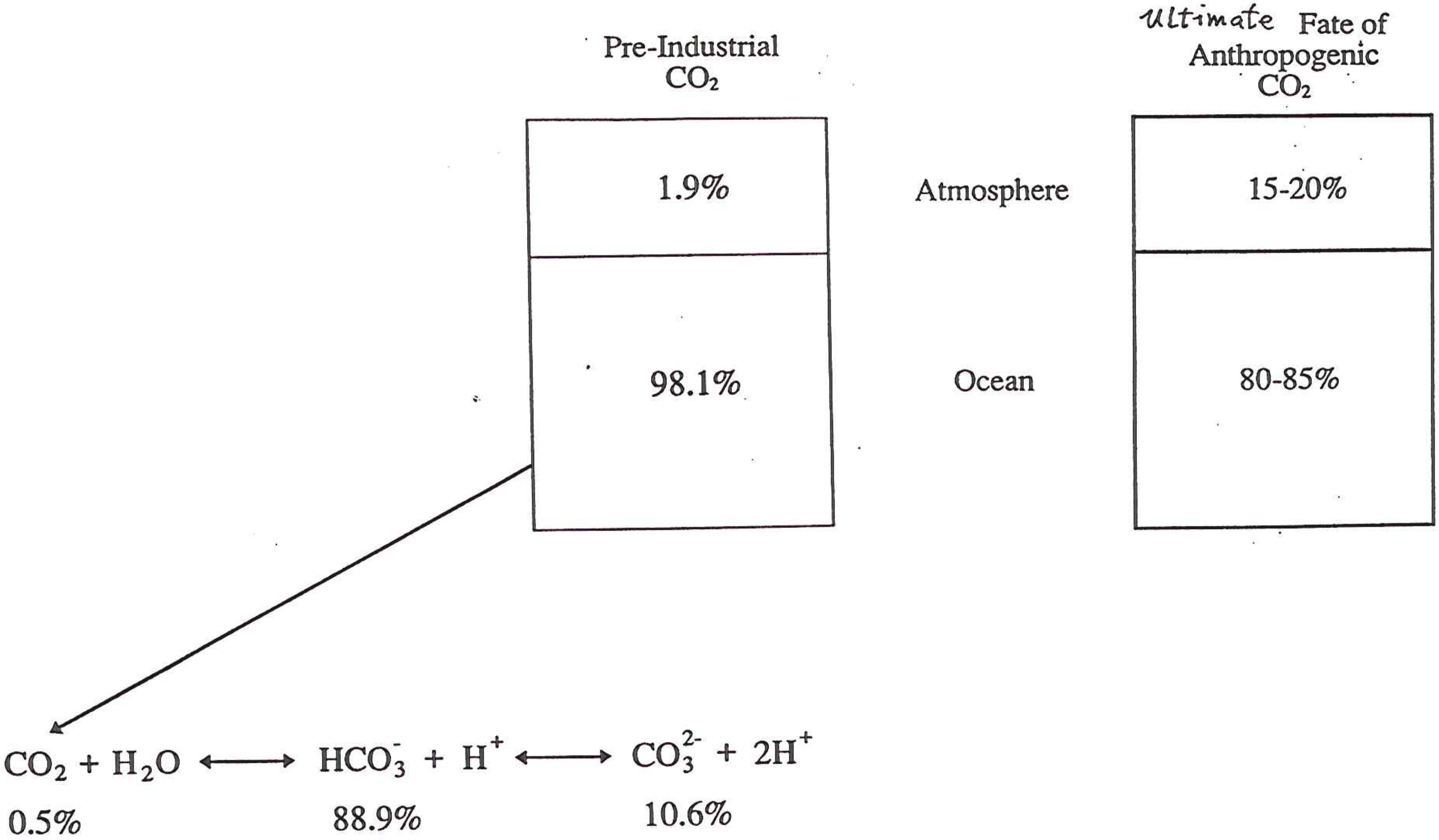
(0.0042)(760 GtC in atmosphere) = 3.2 GtC/yr

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"



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

0.5% 88.9% 10.6%

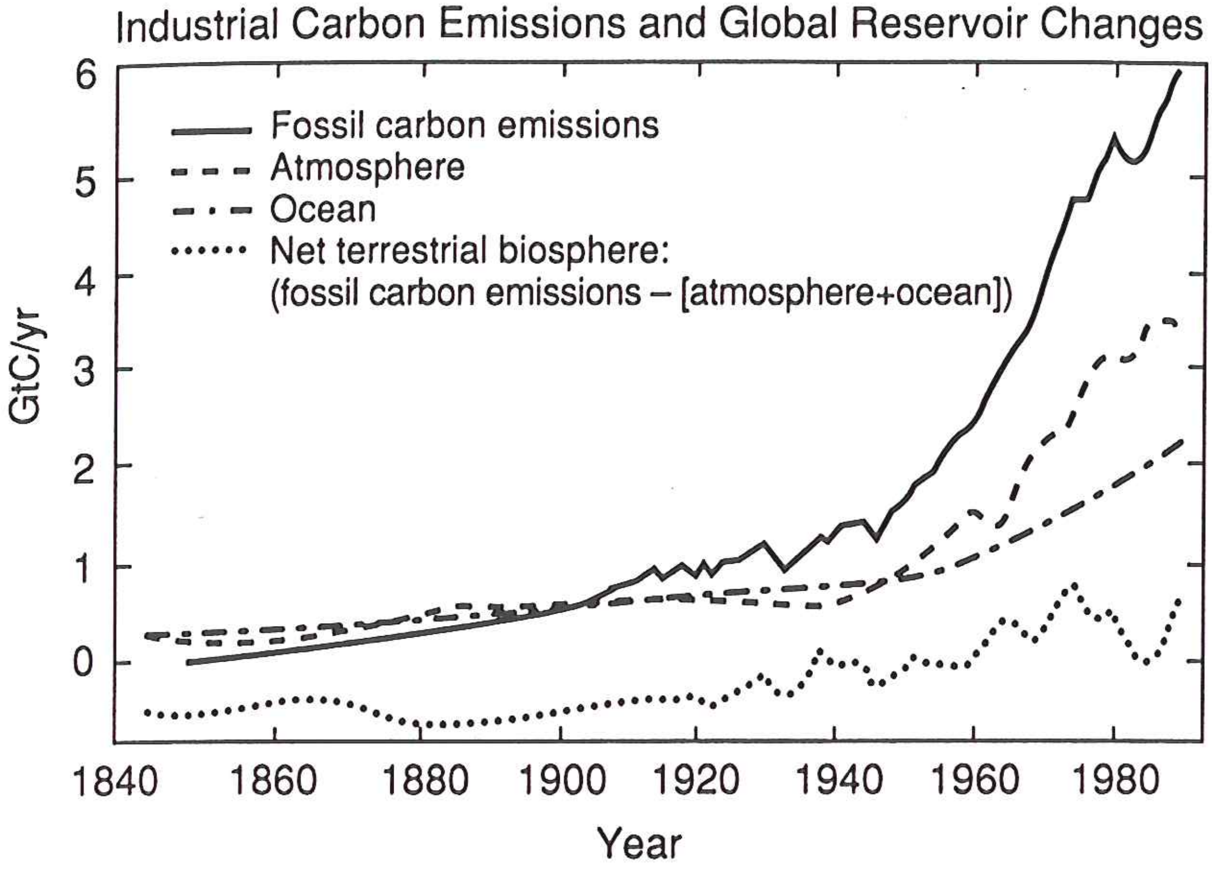
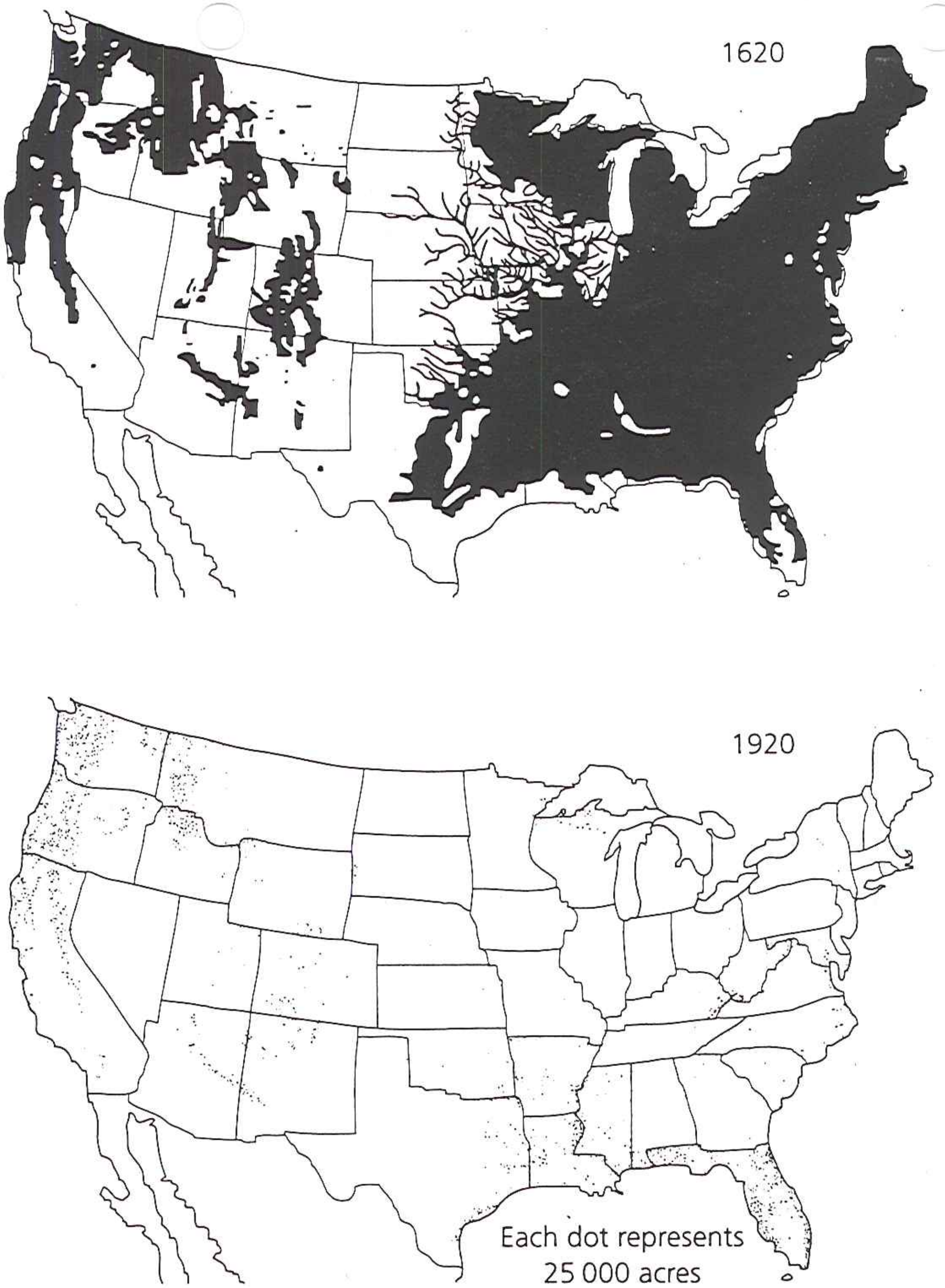


Figure 1.7: Fossil carbon emissions (based on statistics of fossil fuel and cement production), and representative calculations of global reservoir changes: atmosphere (deduced from direct observations and ice core measurements), ocean (calculated with the GFDL ocean carbon model), and net terrestrial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



Loss of forest due to human colonization of North America between 1620 and 1920. After Goudie (1993) [47].

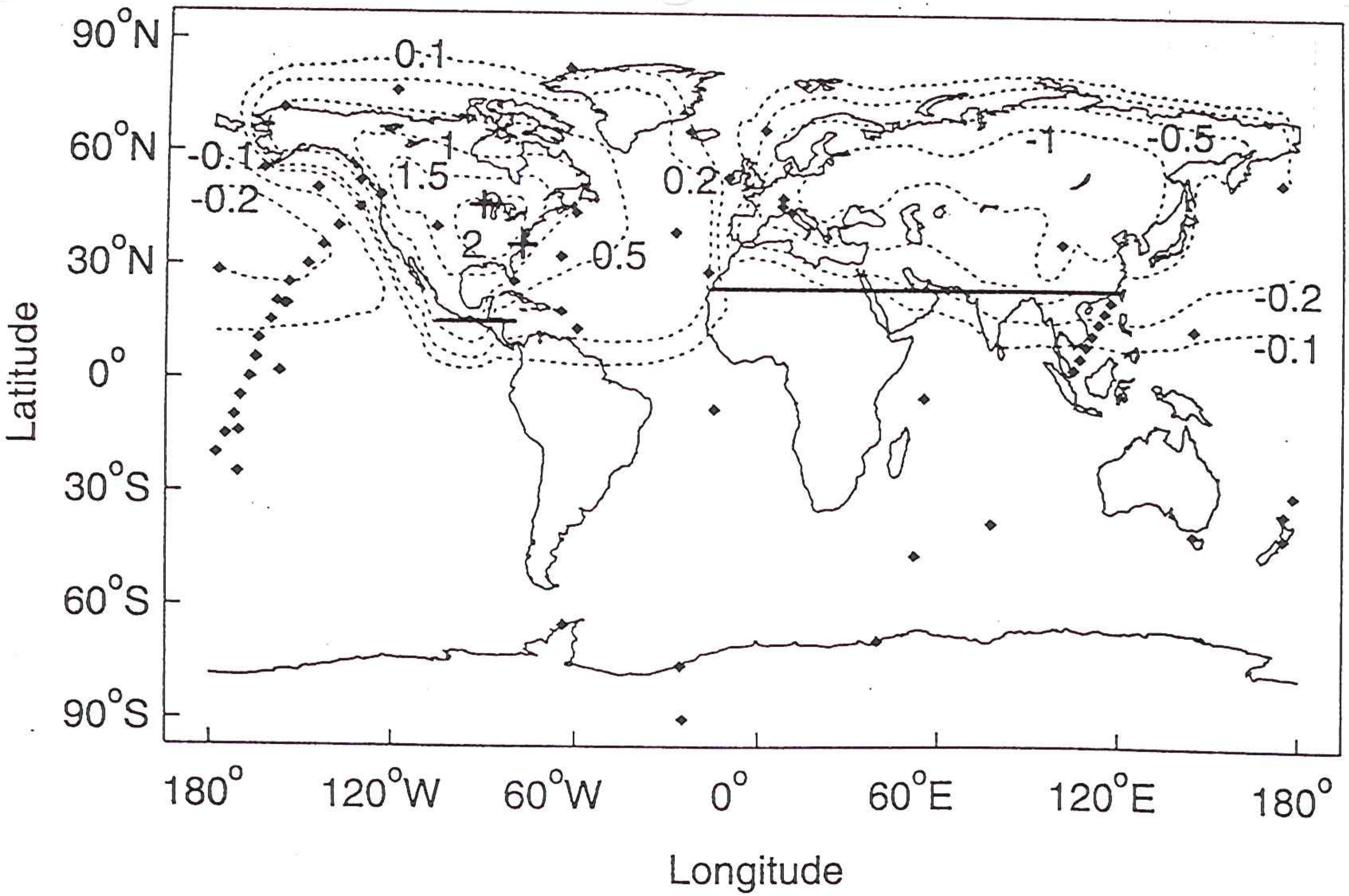


Fig. 1. A map of the atmospheric CO_2 sampling network. Sites are shown as solid diamonds. (The Globalview labels for the Northern Hemisphere stations are given in the legend of Fig. 3). The tall tower sites are shown as crosses. The thick horizontal lines divide the land surfaces into three regions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

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.

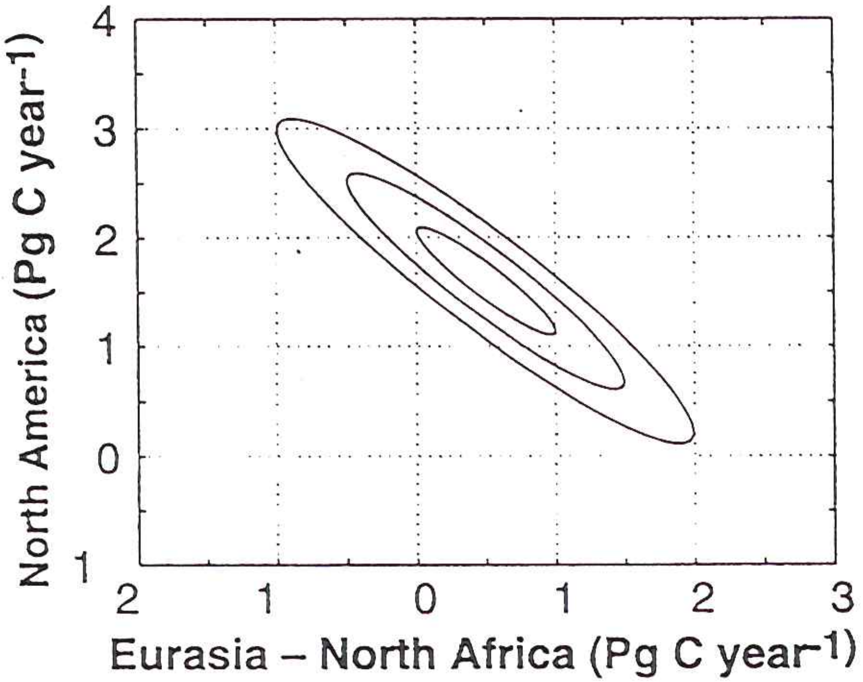


Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

Table 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

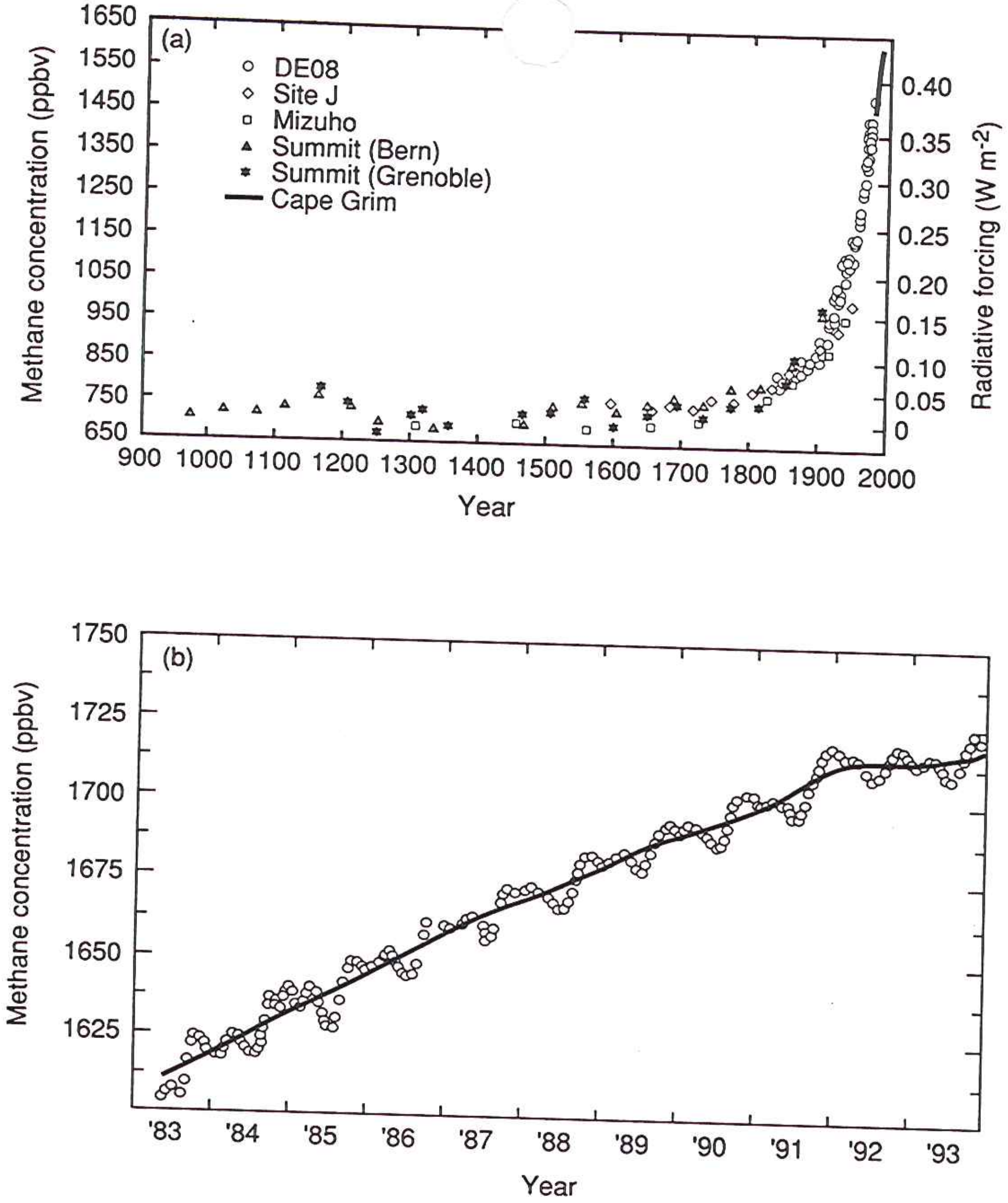


Figure 9: (a) CH_4 concentration derived from Antarctic ice cores over the past 1000 years. Direct observations of CH_4 concentration from Cape Grim, Tasmania, are included to demonstrate the smooth transition from ice core to atmospheric measurements. The radiative forcing resulting from increases in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

SOUTH PACIFIC

NEW ZEALAND: GAS TAX Farmers reacted angrily to a government proposal to tax the flatulence emitted by their cattle and sheep in an effort to reduce the nation's contribution to global warming. Last year New Zealand signed the Kyoto Protocol, agreeing to reduce greenhouse gases. Livestock emissions of methane and nitrous oxide, caused by the complex process of digesting grass, account for more than half the country's greenhouse gases, and the government wants the tax to help pay for research on the emissions. It would cost the average farmer up to $300 a year. Tom Lambie, the president of Federated Farmers, told The New Zealand Herald that the tax was unfair. "As far as I'm aware, we're the only country in the world to impose a levy like this," he said. *(Reuters)*

World Business Briefing, Page B2

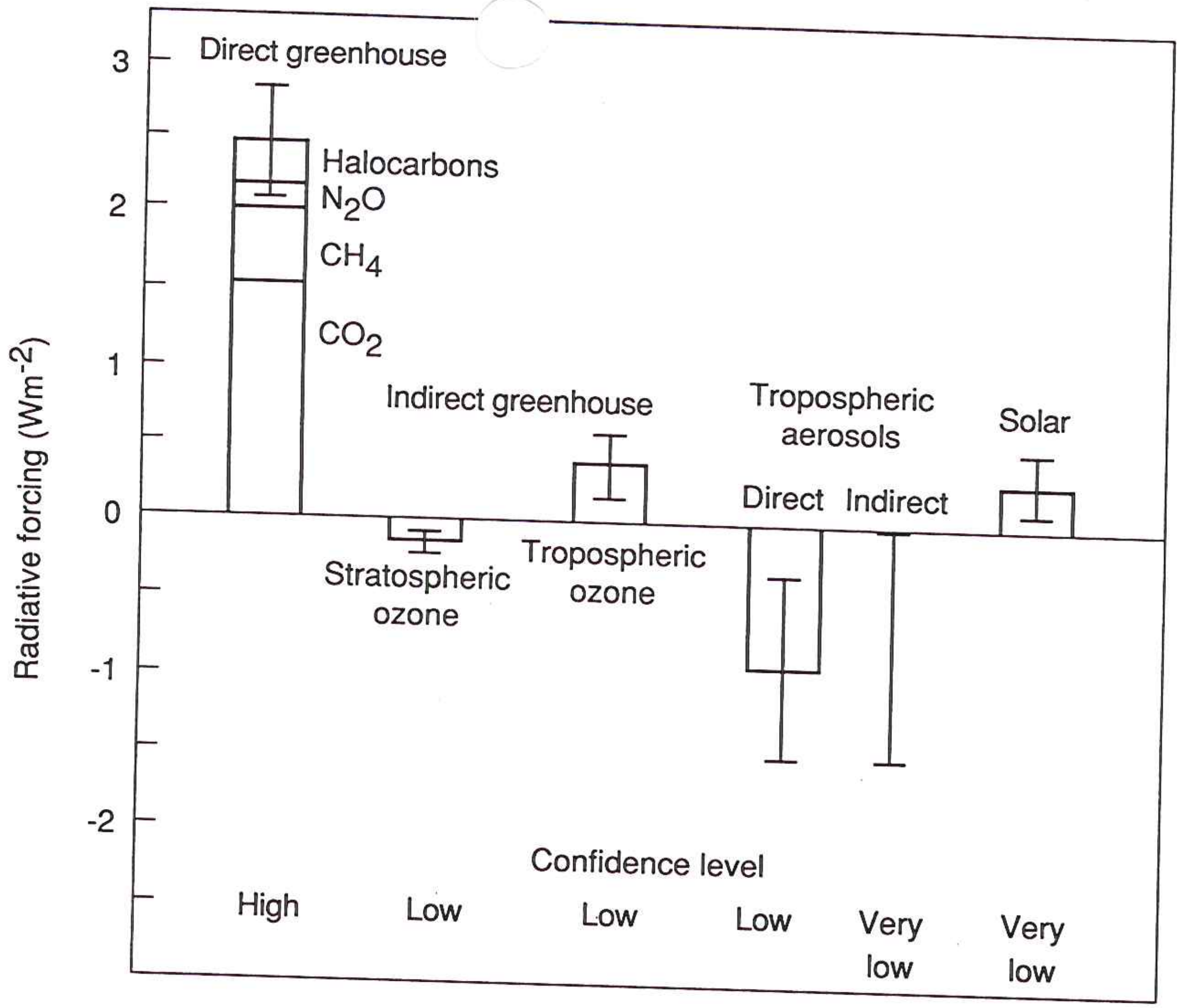


Figure 3: Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial times to the present day and changes in solar variability from 1850 to the present day. The height of the bar indicates a mid-range estimate of the forcing whilst the lines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

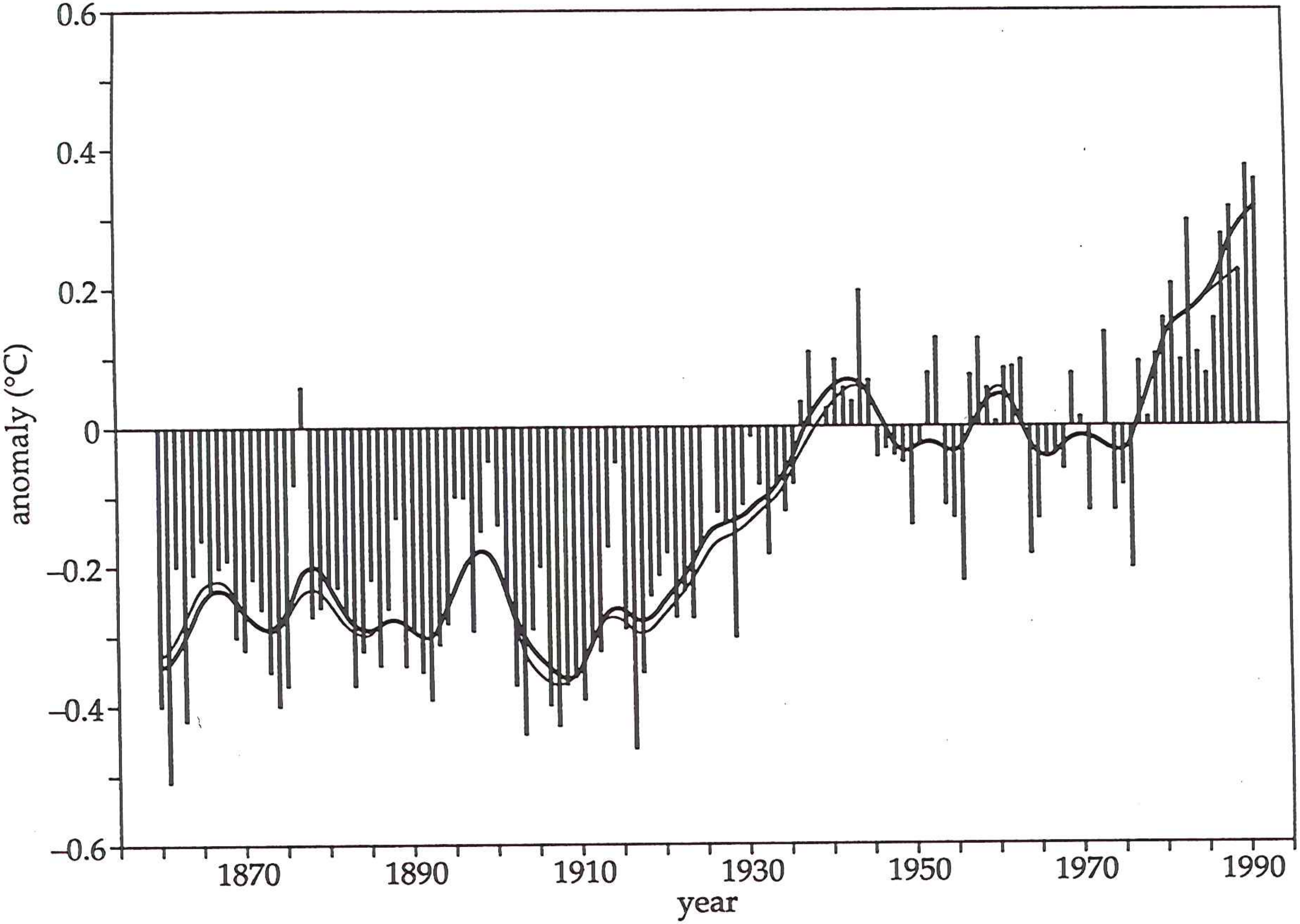


Figure 1.9 Combined land, air and sea surface temperature anomalies between 1861 and 1991, relative to the average temperature 1951–1980. (From IPCC 1992.)

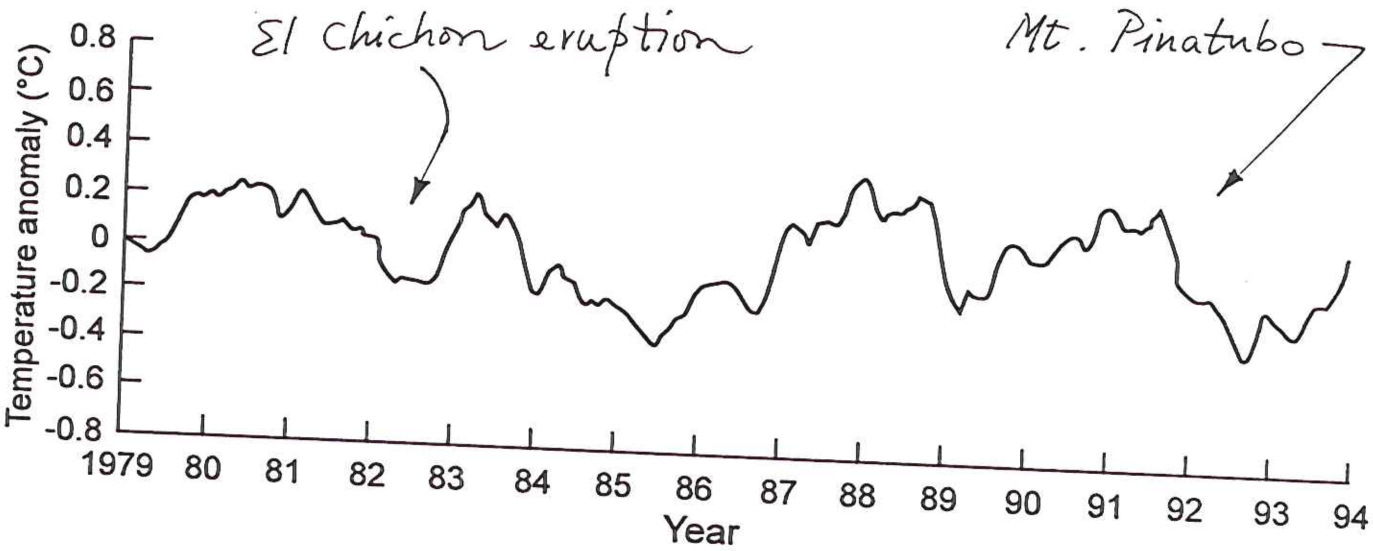
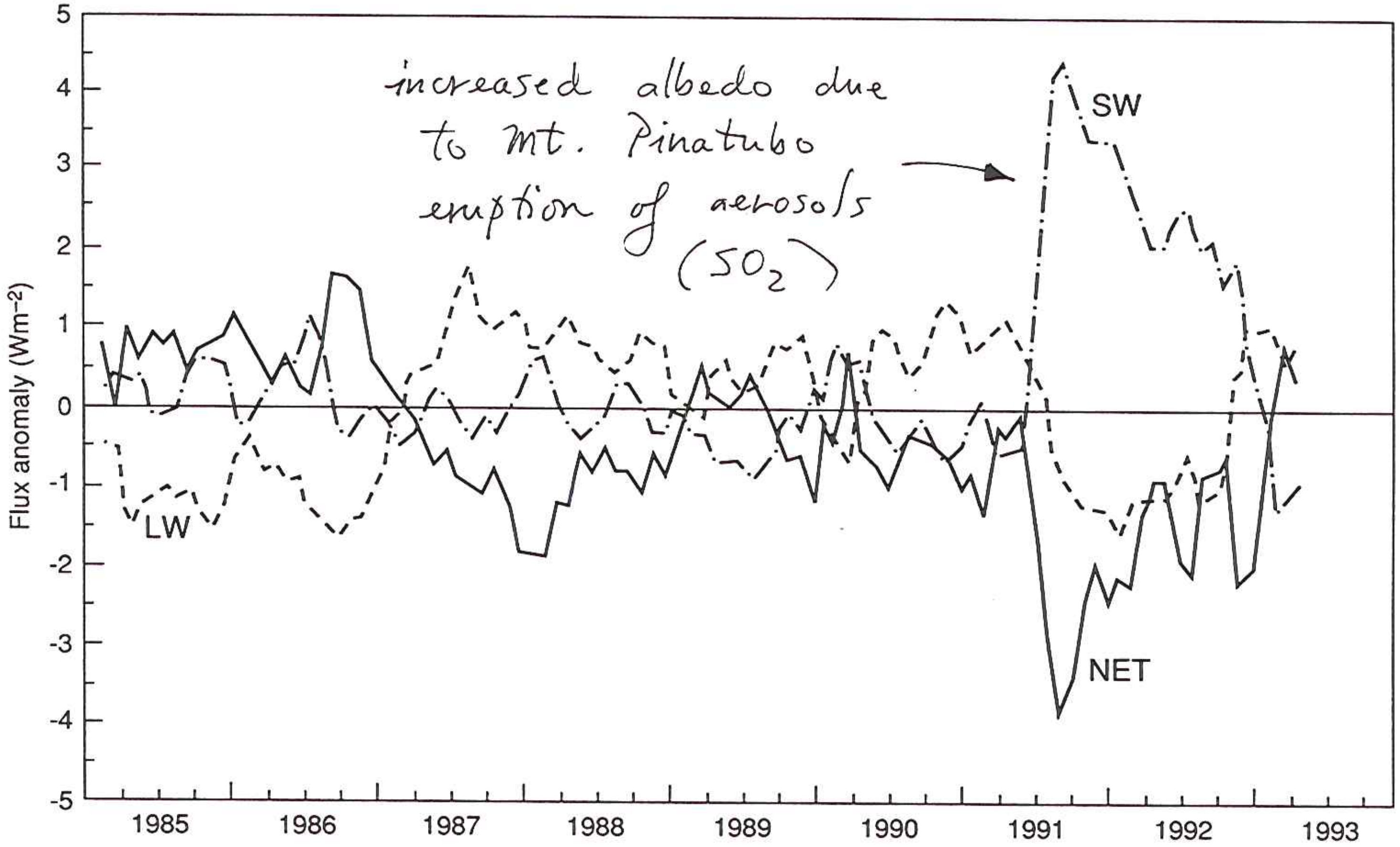


Figure 11.22. Mean global tropospheric temperature anomalies from satellite data (85°S–85°N) from 1979 to 1993. (Data from R. W. Spencer and J. R. Christy; Halpert et al. 1994; see also Kerr 1995)



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.

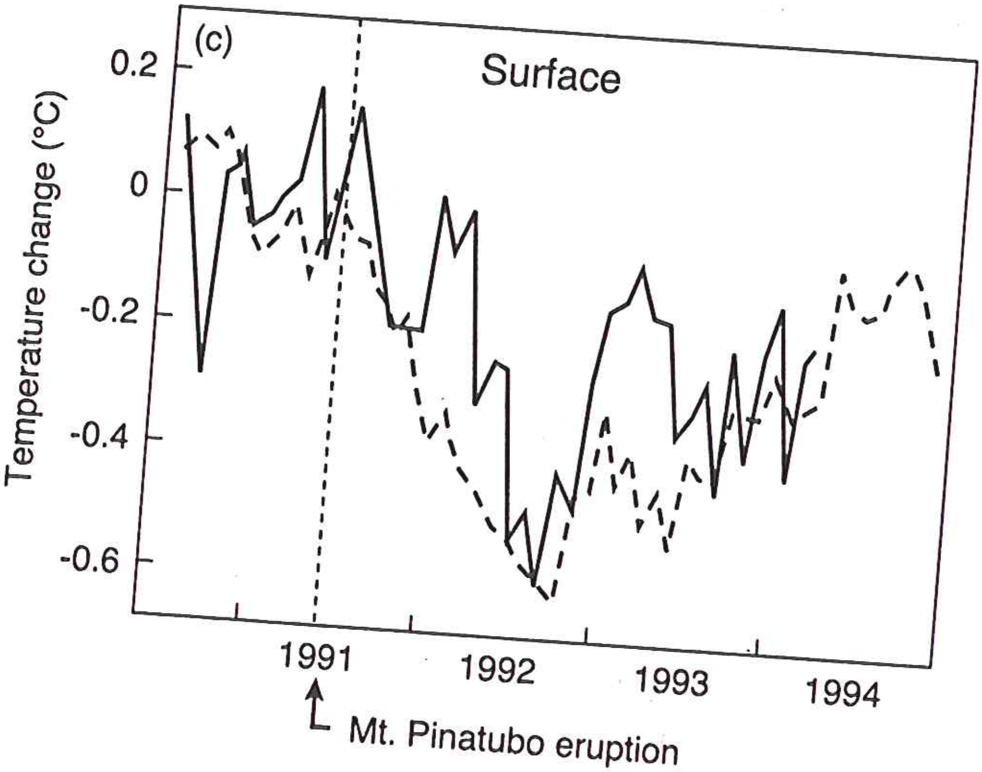
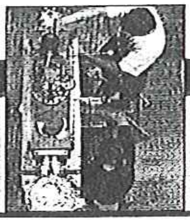
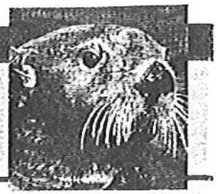


Figure 4.7: Observed and modelled (from the GISS GCM) monthly mean temperature changes over the period of the Mt. Pinatubo eruption (updated from Hansen *et al.*, 1993a). The eruption is indicated by the vertical dashed line. (a) Stratospheric temperatures are from satellite observations and show the 30 mb zonal mean temperature at 10°S and are supplied by M.Gelman, NOAA; the model results are the 10-70 mb layer at 8 to 16°S. The zero is the mean for 1978 to1992. (b) Tropospheric temperatures are from satellite observations and are supplied by J. Christy, Univ of Alabama; the observations and model results are essentially global. The zero is given by the mean for the 12 months preceding the eruption. (c) Surface temperatures are derived from meteorological stations; the observations and model results are essentially global. The zero is given by the mean for the 12 months preceding the eruption. Note that the model results use a simple prediction of the way the optical thickness of the volcanic cloud varied with time, made soon after the eruption, rather than detailed observations of the evolution of the cloud.



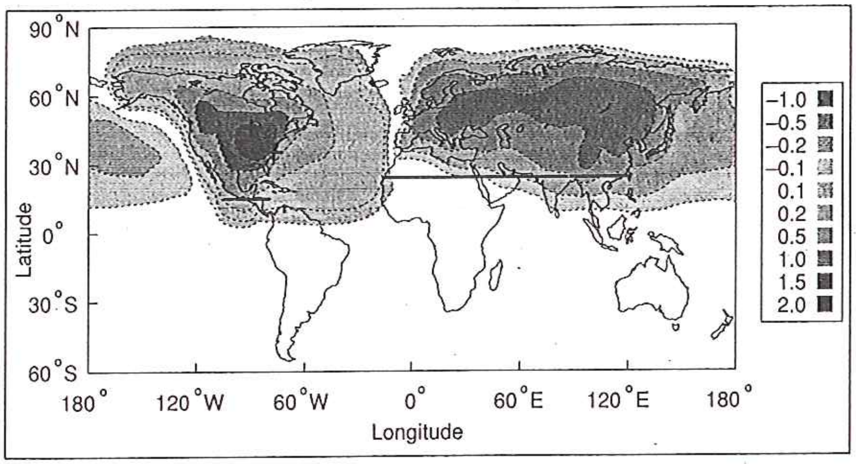


CLIMATE CHANGE

Possibly Vast Greenhouse Gas Sponge Ignites Controversy

As greenhouse warming experts try to predict how much the world's climate may heat up in the next century, they keep bumping up against a mystery: Where does much of the carbon dioxide (CO_2) pumped into the air actually end up? Answering this question could have huge ramifications for nations that ratify the climate change treaty signed in Kyoto, Japan, last December: Countries shown to harbor substantial carbon "sinks" could argue that an ability to soak up excess CO_2 should offset their emissions.

If those arguments prevail, it appears that North America may have drawn the winning ticket in the carbon sink sweepstakes. In what is shaping up as one of the most controversial findings yet to emerge in the greenhouse gas debate, a team of researchers on page 442 of this issue of *Science* presents evidence that North America sops up a whopping 1.7 petagrams of carbon a year—enough to suck up every ton of carbon discharged annually by fossil fuel burning in Canada and the United States. The magnitude of the apparent sink, says team member Jorge Sarmiento of Princeton University, "is going to be a lightning rod for all sorts of criticism."



Disappearing act. Contours show how predicted CO_2 levels (in parts per million) would change if there were no terrestrial uptake in North America. Measured levels decline, rather than increase, from west to east North America, however, implying a large carbon sink.

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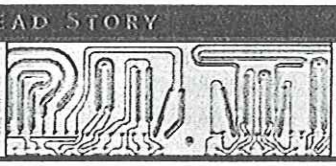
Indeed, critics have already thrown up a fistful of red flags, attacking the study for everything from its methodology to its implications. "There's a huge amount of skepticism about the result," says ecologist David Schimel of the National Center for Atmospheric Research in Boulder, Colorado, who notes that at least one other group has calculated a much smaller North American sink. Moreover, a second paper in this issue—by a group led by Oliver Phillips of the University of Leeds in the United Kingdom (p. 439)—adds to the uncertainty. It points to a carbon sink in tropical South America so large that it is hard to reconcile with the Sarmiento group's results.

Especially worrisome, Schimel and others say, is that groups opposed to the Kyoto treaty will seize on the estimate to argue that the United States doesn't need to reduce its emissions to comply with the accord. "We're all really concerned that many people will find it convenient to accept the result," Schimel says. At the same time, scientists say this sort of calculation is a key step toward honing our understanding of the global carbon cycle. "The authors deserve a lot of credit for sticking their necks out," says climate modeler Inez Fung of the University of California, Berkeley.

At the heart of the debate is a simple math problem, resembling a chronic inability to balance one's checkbook, that has bedeviled scientists for nearly 2 decades. The balance sheet looks like this: Less than half of the 7.1 petagrams of carbon produced by human activity each year stays in the atmosphere. Although about 2 petagrams go into the oceans, another 1.1 to 2.2 petagrams appear to vanish into the land, likely taken up by plants during photosynthesis. Figuring out what's going on—whether the extra CO_2 is spurring faster tree growth, for example, or carbon is disappearing into soils—is crucial to learning whether reforestation and other actions might help stave off warming (*Science*, 24 July, p. 504). "If you understood the mechanism, you'd be in a much better position to say whether the sink will continue," says biogeochemist Richard Houghton of Woods Hole Research Center in Massachusetts.

To get at how much carbon the different land masses are absorbing, Sarmiento and his colleagues with the Carbon Modeling Consortium (CMC), based at Princeton, used an approach called inversion modeling. They first gathered data on atmospheric CO_2 levels taken from 1988 to 1992 at 63 ocean-sampling stations. Next, they divided the world into three regions—Eurasia, North America, and the rest—then fed the CO_2 data into two mathematical models: one that estimates how much carbon the oceans absorb and release, and another that gauges how CO_2 is spread across the globe by wind currents. When they fitted their models to the data, they found that, surprisingly, CO_2 levels dropped off slightly from west to east across North America—even though fossil fuel emissions should boost levels in the east. That meant there must be a big carbon sink in North America.

Straining belief among other experts is the sink's estimated magnitude—1.7 petagrams of carbon per year, plus or minus 0.5 petagrams—roughly equaling the continent's fossil fuel carbon emissions of 1.6 petagrams. "It's hard for me to know where that much carbon could be accumulating in North America," says Houghton. Data from forest inventories suggest the U.S. sink absorbs only 0.2 to 0.3 petagrams of carbon a year. Sarmiento's team suggests that the inventories have missed a lot of forest regrowth on abandoned farmland and formerly logged forests in the east fertilized by CO_2 or nitrogen pollution, and that they fail to account for carbon stored in soils and wetlands. But the result also suggests that Eurasia's immense forests are taking up only a fifth as much carbon as U.S. forests. "Ecologically, it seems al-



391 Greenhouse shreds Antarctic ozone

392 Far-out galaxies

LEAD STORY 401 A credit-card–sized biolab

most incomprehensible," Schimel says.

Several modelers contend that the study is riddled with uncertainties. For one thing, the two models used to gauge carbon flux "could easily be off by just a little bit, and you get a very different conclusion," says Fung. The results could also be skewed by a dearth of data from the North Atlantic, as the authors note in their paper. For example, the group threw out readings off Sable Island, Nova Scotia, because the data were unreliable, says team member Pieter Tans of the National Oceanic and Atmospheric Administration. Factoring in Sable Island, the sink shrinks by 30%.

Even if the results do hold up, observers note, the CMC study's time period includes the 1991 Mount Pinatubo eruption, which led to cooler, wetter conditions and a much higher global carbon uptake than usual. "Some of this sink must clearly be ... transient," says Martin Heimann, a modeler at the Max Planck Institute for Biogeochemistry in Jena, Germany. And the findings clash with those from a team led by Peter Rayner of Monash University in Australia, which calculates a North American sink of only 0.6 petagrams of carbon from 1988 to 1992—about one-third the CMC group's estimate. The Australian group's results will be published next year in *Tellus*.

The CMC team acknowledges that its results strain credibility. "I have trouble quite believing" the size of the sink, says Tans, adding that "We're pushing the data pretty far." But, says Sarmiento, "we've really carefully analyzed the data in a lot of different ways." U.S. Geological Survey geochemist Eric Sundquist agrees: "The paper is a credible and rigorous interpretation of the available data."

More and better data, including direct measurements of carbon storage and flux over land, will be needed to narrow the gap between the two studies. Already, this approach has turned up a big surprise: According to the U.K. group's results, undisturbed tropical forests in South America are getting thicker and may account for about 40% of the missing sink, a figure seemingly at odds with the CMC group's inversion results. The study is the first to pool data from measuring carbon storage, or biomass, over 2 decades at over 150 tropical forest plots worldwide. "This illustrates the types of studies that really need to be integrated," says Sundquist.

Before this research has time to mature, however, the possibly vast North American carbon sink could be the subject of heated debate in climate treaty implementation talks next month in Buenos Aires, Argentina. If the CMC team's findings are accurate, "the most obvious conclusion" would be that "there's no need for the U.S. and Canada to curb emissions," says Heimann. Indeed, Steven Crookshank of the American Petroleum Institute says the study "calls into question the scientific basis on which we're making these decisions, when we still don't know if the United States is even emitting any carbon in the net."

But some observers argue that a large North American sink should not be an excuse to go easy on emission controls. Maturing forests eventually stop storing carbon, so "this part of the missing sink [won't] be with us forever or even much longer," says atmospheric physicist Michael Oppenheimer of the Environmental Defense Fund in New York City. "The existence of the sink isn't important. What's important is the changes in the sink."

–JOCELYN KAISER

SCIENCE EDUCATION

California Adopts Controversial Standards

Third-graders in California will be taught about the periodic table, and sixth-graders will learn about Earth's "lithospheric plates" under a new set of standards* approved last week by the state Board of Education. The standards—which will be used to revise the state curriculum, set guidelines for textbooks, and develop statewide tests—have been sharply attacked by many science education reformers, who contend that they focus too much on detailed knowledge and too little on concepts. Although the board's action appears to put an end to the controversy, critics are hoping that the winner of next month's gubernatorial race will revive the debate.

The standards reflect California's first attempt to spell out what students in kindergarten through 12th grade should learn about science. They follow on the heels of mathematics standards that were even more hotly contested before their adoption last December (*Science*, 29 August 1997, p. 1194). New tests for the state's 5.5 million students are scheduled to be ready in 2000—the same year public school textbooks will have to meet new guidelines. Those are expected to influence science teaching across the country, as California represents more than 10% of the national textbook market.

Last Friday's unanimous vote by the board came after a final flurry of lobbying and letter-writing by more than a dozen scientific societies (including the American Association for the Advancement of Science, which publishes *Science*). Some of these groups offered to help rewrite the final draft to bring it into line with National Science Education Standards issued in 1996 by the National Academy of Sciences (NAS). "It doesn't match the [national] standards in any way," says NAS President Bruce Alberts. He and others believe that the state standards contain so much factual material that teachers will be forced to skip more in-depth learning activities that would give students a better understanding of the scientific process.

But others praise the California standards as a challenging but realistic set of ex-

WHAT THE BATTLE'S ABOUT

NAS STANDARDS (Physical Science, grades K-4)

"Materials can exist in different states—solid, liquid, and gas. Some common materials, such as water, can be changed from one state to another by heating or cooling."

[Elements are introduced in grades 5-8; atoms are covered in grades 9-12.]

CALIFORNIA STANDARDS (Physical Science, grade 3)

"Matter has three forms: solid, liquid, and gas.... Evaporation and melting are changes that occur when the objects are heated.... All matter is made of small particles called atoms, too small to see with our eyes.... There are over 100 different types of atoms which are displayed on the periodic table of elements."

Standard deviation. California's new science standards introduce the periodic table in grade 3, while those developed by the National Academy of Sciences discourage use of the terms "atom" and "molecule" with students younger than high school.

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* See http://www.ca.gov/goldstandards; revisions are at http://www.cde.ca.gov/board/board.html

SOURCES: NATIONAL SCIENCE EDUCATION STANDARDS; CALIFORNIA ACADEMIC STANDARDS COMMISSION; PHOTO: VISUALS UNLIMITED

CREDIT: S. FAN *ET AL.*

Changes in the Carbon Balance of Tropical Forests: Evidence from Long-Term Plots

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William F. Laurance, Percy V. Núñez, Rodolfo M. Vásquez,
Susan G. Laurance, Leandro V. Ferreira, Margaret Stern,
Sandra Brown, John Grace

The role of the world's forests as a "sink" for atmospheric carbon dioxide is the subject of active debate. Long-term monitoring of plots in mature humid tropical forests concentrated in South America revealed that biomass gain by tree growth exceeded losses from tree death in 38 of 50 Neotropical sites. These forest plots have accumulated 0.71 ton, plus or minus 0.34 ton, of carbon per hectare per year in recent decades. The data suggest that Neotropical forests may be a significant carbon sink, reducing the rate of increase in atmospheric carbon dioxide.

Tropical forests contain as much as 40% of the C stored as terrestrial biomass (*1*) and account for 30 to 50% of terrestrial productivity (*2*). Therefore, a small perturbation in this biome could result in a significant change in the global C cycle (*3, 4*). Recent micrometeorological research suggests that there is a net C sink in mature Amazonian forests (*5, 6*), but the ability to draw firm conclusions is hampered by the limited spatial and temporal extent of these measurements. Another approach, applying atmospheric transport models to measured global distributions of CO_2, O_2, and their isotopes (*7*), has yielded conflicting results. We report a third approach to explore the role of mature tropical forests in the global C cycle, namely, the use of permanent sample plots (PSPs). PSPs, established by foresters and ecologists to monitor tree growth and mortality, have the potential to yield C accumulation estimates that are at once both geographically extensive and of high spatial and temporal resolution.

We compiled data on basal area (cross-sectional area of trees per unit ground area) from mature tropical forest plots (*8*) that meet appropriate a priori criteria (*9*). Basal area of trees is a well-substantiated surrogate measure of total biomass in tropical forests (*10*), so changes due to tree growth and mortality provide an effective measure of changes in biomass. We tested for changes in mature tropical forest biomass in each of four nested regions: the humid tropics (153 plots), the humid Neotropics (120 plots), the humid lowland Neotropics (108 plots), and Amazonia (97 plots) (*11*). These plots represent more than 600,000 individual tree measurements tropics-wide.

We conducted two analyses with the information available. For each region, we first calculated the mean rate of change in tree basal area across sites, based on the difference between the initial and final census at each geographically distinct site (*12*). Sites may contain one or more floristically and edaphically similar plots (*13*). In the second analysis, we estimated basal area change as a function of calendar year and derived an estimate of regional net accumulated biomass through time. Data for this approach were derived for each site by first computing differences between each successive census, then by linear interpolation between successive censuses for years when measurements were not taken, and finally for each year by averaging change across all contributing plots. Measurement errors were corrected by comparing multiple measurements of the same tree over time (*14*). Basal area values were converted to aboveground biomass estimates by using an allometric model developed for lowland forest in central Amazonia and by using correction factors to account for the biomass of lianas and small trees (*15*).

Biomass has increased in mature forest sites in the humid Neotropics (1.11 ± 0.54 t ha^{-1} $year^{-1}$; mean ± 95% confidence intervals), the humid lowland Neotropics (1.08 ± 0.59 t ha^{-1} $year^{-1}$), and in Amazonia (0.97 ± 0.58 t ha^{-1} $year^{-1}$) (*16*). The entire pantropical dataset also shows an increase in biomass (0.77 ± 0.44 t ha^{-1} $year^{-1}$), but the signal is dominated by the Neotropical pattern, and there has not been a significant change in Paleotropical sites (tropical Africa, Asia, Australia) (−0.18 ± 0.59 t ha^{-1} $year^{-1}$) (*17*). In the Neotropics (tropical Central and South America), the mean value of biomass change has been positive for most years since widespread PSP monitoring began (*18*). In Amazonia, where most inventories are located, plots have on average gained biomass in most years since at least the late 1970s (Fig. 1). By 1990, mature forest sites in all three nested Neotropical regions had on average accumulated substantial biomass (Fig. 2).

These results show that (i) there is considerable spatial and temporal variability in rates of biomass change, yet (ii) on average,

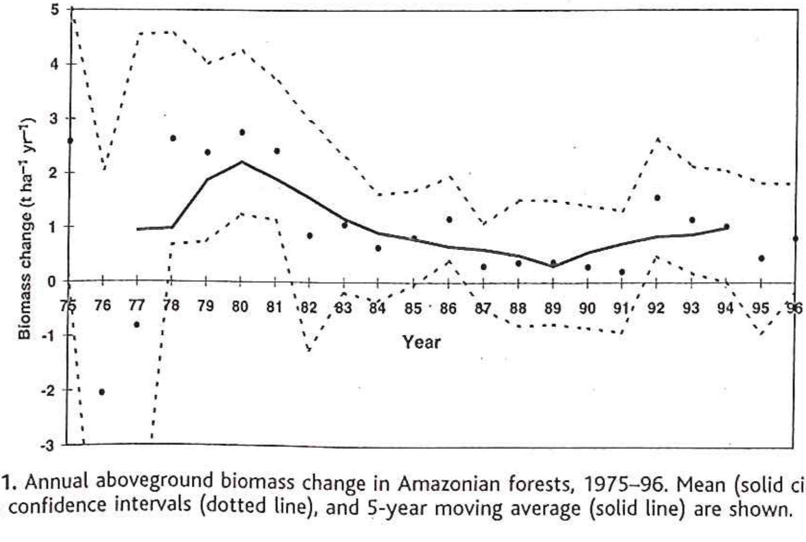

Fig. 1. Annual aboveground biomass change in Amazonian forests, 1975–96. Mean (solid circles), 95% confidence intervals (dotted line), and 5-year moving average (solid line) are shown.

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plots have gained biomass, and (iii) the increase has been especially marked in lowland Neotropical sites. There has been no statistically detectable change in biomass in African and Asian plots, but our coverage of these areas (18 sites) is sparser than in the Neotropics (50 sites), so we concentrate our discussion on the Neotropics. If the difference between Neotropical and Paleotropical forests is genuine, it may reflect differing climatic factors or perhaps greater human disturbance in the more densely populated Paleotropics (*19*).

Before extrapolating these results to the biomass of Neotropical forests as a whole, it is important to consider whether the PSPs were representative of the broader region. Neotropical forests are heterogeneous (*20*), and our dataset spans much of the natural variation in Amazonian forests (*21*). The number of extra-Amazonian lowland and montane samples also corresponds to the approximate coverage of each region (*22*). Recent debate (*23*) has centered on two potential problems in monitoring: (i) research activity having a negative impact on tree survivorship and growth and (ii) plots becoming increasingly subject to edge effects as surrounding forest is fragmented (*24*). These effects would increase mortality relative to growth, thus causing a decline in measured biomass—the opposite of our result. A further possibility is that there could be a bias in the PSPs compared to the surrounding forest, by systematic avoidance or underreporting of forests that underwent natural catastrophic disturbances or smaller scale disturbance due to localized tree death. Although it is difficult to quantify such a bias, there is little evidence for it in our dataset (*25*), and the increase in biomass is larger than can be accounted for simply by the dynamics of a few large trees (*26*).

Our results are therefore indicative of a widespread increase in the biomass of surviving Neotropical forests over recent decades. There are a number of mechanisms that may explain this change: (i) a response to continental-scale cyclical climate change; (ii) recovery from widespread disturbance, either natural or anthropogenic; (iii) enhanced forest productivity due to a secular change in climate or increased nutrient availability.

Because Earth's climate fluctuates, forest stocks of C might be responding to past climatic events. The El Niño–Southern Oscillation (ENSO) may be one long-term driver of cyclical changes in forest dynamics (*27*). In El Niño years, most of Amazonia receives below-normal rainfall (*28*), but our data show that Amazon forests gained biomass before, during, and after the intense 1982–83 ENSO (Fig. 1). It is possible that regional forest biomass is recovering from earlier greater disturbances, either from drought or from the impacts of indigenous peoples who have experienced steep population declines since the 16th century (*29*). The biomass increase could also be a response to recent anthropogenic global change. There is some evidence for an increase in temperate and tropical forest productivity (*30*), and even mature ecosystems may gain biomass if plant productivity is stimulated (*4*). Candidate factors for nutrient fertilization include increasing atmospheric CO_2 (*31*) and increased N and P deposition from Saharan dust (*32*) and biomass burning (*33*).

To estimate regional C sequestration rates, we first converted aboveground biomass into C stocks, using allometric data obtained in central Amazonia (*34*). The increase in biomass on Amazonian plots is equivalent to a net uptake of 0.62 ± 0.37 t C ha^{-1} $year^{-1}$. Multiplying this by the estimated area of humid forest in lowland Amazonia (*22*) produces a mature forest biomass C sink of 0.44 ± 0.26 Gt C $year^{-1}$. Similarly, the estimated annual C sink in lowland Neotropical humid forest is 0.52 ± 0.28 Gt C; it is 0.62 ± 0.30 Gt C for all mature humid neotropical forests. Our method suggests a lower C uptake rate than estimates from eddy covariance studies in Rondônia (1.0 t ha^{-1} $year^{-1}$) (*2*) and near Manaus (5.9 t ha^{-1} $year^{-1}$) (*6*). The discrepancy may reflect the limited spatial and temporal extent of eddy covariance measurements, or else be indicative of significant in-

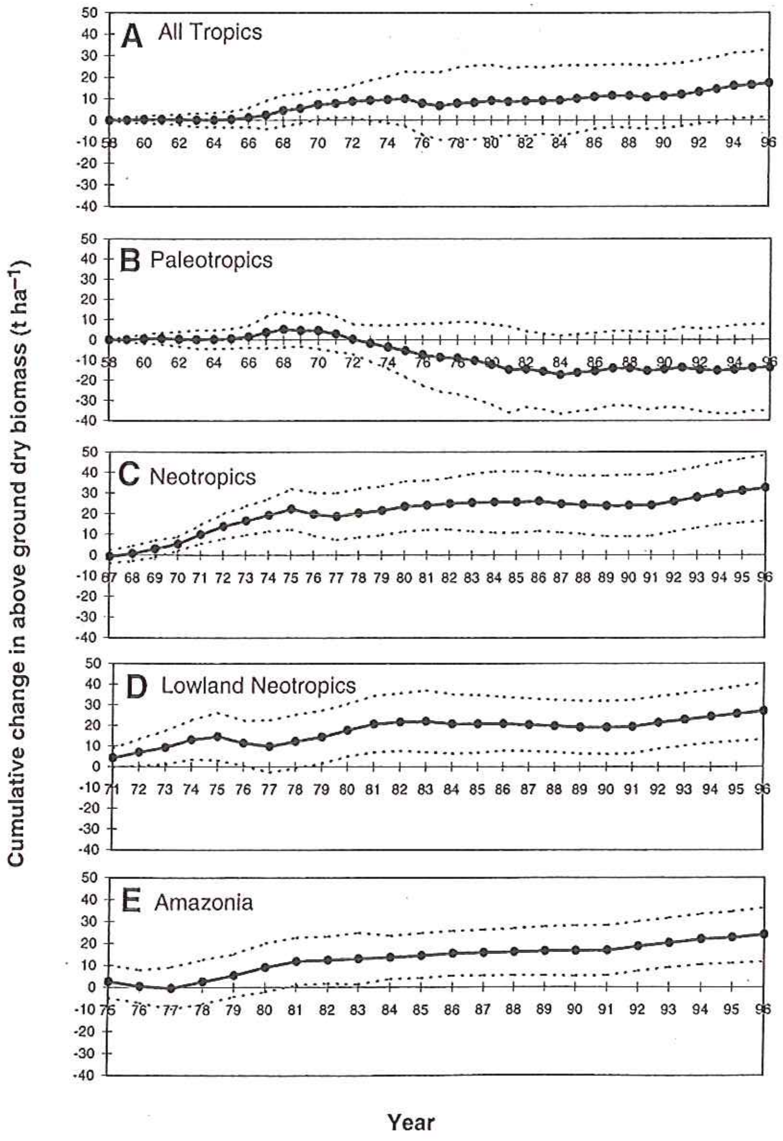

Fig. 2. Cumulative aboveground net biomass change (tons per hectare per year) in humid forests in: (**A**) the Tropics since 1958; (**B**) the Paleotropics (tropical Africa, Asia, Australia) since 1958; (**C**) the Neotropics (tropical Central and South America) since 1967; (**D**) the lowland Neotropics since 1971; (**E**) Amazonia since 1975. Annual mean (solid line) and 95% confidence interval (dotted line) values are based on the cumulative changes in individual sites since the first year and are scaled by *a*/*b*, where *a* = the cumulative time elapsed since the first year and *b* = the mean monitoring period per site up to each year end.

creases in the necromass and soil pools (*35*), which are not accounted for in our analysis.

Our results suggest that mature Neotropical forest biomass may account for ~40% of the so-called "missing" terrestrial C sink (*36*). Hence, intact forests may be helping to buffer the rate of increase in atmospheric CO_2, thereby reducing the impacts of global climate change. However, the C sink in mature forests appears vulnerable to several factors. There is likely to be an upper limit to the biomass a forest stand can hold. Moreover, deforestation, logging (*37*), increased fragmentation and edge-effect mortality (*23, 24*), regional drying and warming (*38*), and possible intensification of El Niño phenomena (*39*) may limit and even reverse the sink provided by mature forest. A dedicated large network of permanent biomass plots could provide vital insight into the future role of tropical forests in the global C cycle.

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8. Sequential basal area data were sourced in three ways: (i) from unpublished plots in Peru, Brazil, and Venezuela censused by the authors and colleagues; (ii) by asking others responsible for monitoring mature plots for permission to use their unpublished data; and (iii) from the literature. Basal area (*BA*, in square meters) is related to diameter (*D*, in meters) by $BA = \Pi (D/2)^2$.
9. Mature tropical forest data were included where living trees ≥10 cm in diameter were measured either at 1.3 m (nonbuttressed trees) or immediately above buttress roots. Sites that experienced natural disturbances before or during the inventory period were generally included, but cyclone-prone forests (such as Puerto Rico or Australia) were excluded to avoid biases in timing; most such plots were either recensused immediately after cyclones hit or else are established in areas recovering from cyclones [see also review by E. V. J. Tanner, J. R. Healey, V. Kapos, *Biotropica* **23**, 513 (1991)]. This exclusion was conservative; biomass increased in the two cyclone-forest sites with published long-term basal area data [T. R. Crow, *ibid.* **12**, 42 (1980); D. I. Nicholson, N. Henry, J. Rudder, *Proc. Ecol. Soc. Aust.* **15**, 61 (1988)]. Plots in forest fragments ≤100 ha and plots that suffered mass mortality by logging or deforestation before or during the inventory period were also excluded.
10. For example, J. M. Pires and G. T. Prance, in *Amazonia*, G. T. Prance and T. E. Lovejoy, Eds. (Pergamon, Oxford, 1985), pp. 109–145; S. Brown, A. J. R. Gillespie, A. E. Lugo, *For. Sci.* **35**, 881 (1989); *Can. J. For. Res.* **21**, 111 (1991); I. Foster Brown, D. C. Nepstad, I. de O. Pires, L. M. Luz, A. S. Alechandre, *Environ. Conserv.* **19**, 307 (1992); A. J. R. Gillespie, S. Brown, A. E. Lugo, *For. Ecol. Manage.* **48**, 69 (1992).
11. "Humid tropics" includes forest receiving >1500 mm precipitation annually; "lowlands" includes forest <500 m above mean sea level; "Amazonia" includes humid forest within the phytogeographical region of Amazonia, encompassing Amazonian Brazil, Colombia, Ecuador, Peru, Bolivia, the Guianas, and contiguous moist forest in Venezuela, excluding nonforest vegetation.
12. Data table and data references are available as supplementary material at the *Science* Web site. (www.sciencemag.org/feature/data/976299.shl)
13. Mean individual plot size per site = 1.87 ha; data from plots <0.2 ha were pooled.
14. Excessive declines or increases in diameter of trees reported in individual censuses indicate human measurement error and were corrected by interpolating between prior and subsequent censuses.
15. The relationship between tree basal area (*BA*, in square meters per hectare) and fresh aboveground biomass of trees ≥10 cm diameter (*AGFB*, in tons per hectare) has the linear form $AGFB = 66.92 + 16.85(BA)$, with $r^2 = 0.85$, based on destructive harvesting of 319 trees at site 9. The relationship was tested and found to be appropriate at another site in eastern Amazonia [T. M. Araujo, N. Higuchi, J. A. Carvalho Jr., *An. Acad. Bras. Cienc.* (1996)]. Correction factors were included for the biomass of trees with diameter <10 cm (× 1.062), on the basis of the biomass-DBH (diameter at breast height) distribution, and for lianas with diameter ≥1 cm (× 1.037), on the basis of liana/tree biomass comparisons in Amazonian forests [E. E. Hegarty and G. Caballé, in *The Biology of Vines*, F. E. Putz and H. E. Mooney, Eds. (Columbia Univ. Press, New York, 1991), pp. 313–336]. Other generally minor components of plant biomass such as stranglers, epiphytes, shrubs, and herbs were not considered. The proportion of water in *AGFB* (40%) was determined from the destructive sampling of 38 trees and the partial sampling of 100 trees at site 9.
16. Neotropics: $n = 50$ sites, 38 with positive change, $P < 0.001$; lowland Neotropics: $n = 45$ sites, 34 with positive change, $P < 0.01$; Amazonia: $n = 40$ sites, 30 with positive change, $P < 0.01$. *P* values are for two-tailed binomial tests; the one Amazon site with no change was treated as negative change.
17. All tropics: $n = 68$ sites, 48 with positive change, $P < 0.01$; Paleotropics: $n = 18$ sites, 10 with positive change, not significant. *P* values are for two-tailed binomial tests.
18. For years in which ≥5 sites were monitored, the mean change was positive in 24 of 30 years 1967–96 for the Neotropics ($P < 0.01$), in 21 of 26 years 1971–96 for the lowland Neotropics ($P < 0.01$), in 20 out of 22 years 1975–96 for Amazonia ($P < 0.001$), in 13 of 30 years 1958–87 for the Paleotropics (not significant), and in 36 of 41 years since 1956 for all tropical forests ($P < 0.001$). *P* values are for two-tailed binomial tests.
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21. Nonflooded forests on low- to medium-fertility pre-Holocene substrates cover 65 to 70% of Amazonia [J. M. Pires, in *Tropical Forest Ecosystems* (UNESCO, Paris, 1978), pp. 607–627] and comprise 70% of our Amazonian sites. Other extensive Amazonian forest types (on alluvial, white sand, and swampy substrates) feature in the dataset in proportion to their region-wide abundance.
22. Estimates of humid tropical forest areas vary according to definition. We use the 1990 area estimates from the Food and Agricultural Organisation [*FAO Forestry Paper 112* (FAO, Rome, 1993)], combining areas described as tropical rain forest, moist deciduous forest, and hill and montane forest to calculate humid Neotropical forest area in the lowlands (7,486,150 km^2) and in total (8,705,100 km^2). Our estimate of lowland Amazonian forests (7,116,280 km^2) is based on combining the lowland humid forest figures for Brazil, Bolivia, Colombia, Ecuador, French Guyana, Guyana, Peru, Suriname, and Venezuela. The area is dominated by the Amazonian hylaea, but also includes small areas of lowland forest along the Pacific and Atlantic coasts.
23. See also R. O. Bierregaard, T. E. Lovejoy, V. Kapos, A. Santos, R. Hutchings, *Bioscience* **42**, 859 (1992); O. L. Phillips, *Science* **268**, 894 (1995); D. Sheil, *ibid.*, p. 894; *For. Ecol. Manage.* **77**, 11 (1995); R. Condit, *Trends Ecol. Evol.* **12**, 249 (1997); L. V. Ferreira and W. F. Laurance, *Conserv. Biol.* **11**, 797 (1997); O. L. Phillips and D. Sheil, *Trends Ecol. Evol.* **12**, 404 (1997); O. L. Phillips, P. Nuñez V., M. Timaná, *Biotropica*, in press.
24. Fragmented Amazonian forests can experience precipitous declines in biomass after isolation [W. F. Laurance *et al.*, *Science* **278**, 1117 (1997)], and edge effects have been suggested to extend up to 1000 m in from forest margins [D. Skole and C. Tucker, *ibid.* **260**, 1905 (1993)]. We excluded a priori any plots in fragments ≤100 ha, but some Neotropical sites are in larger islands or narrow peninsulas of forest (sites 1, 42, 43), are close to forest edges abutting on large areas that have been deforested before or during the monitoring periods (sites 2, 34), or are characterized by both these conditions. The mean rate of biomass change in these sites is -0.42 t ha^{-1} $year^{-1}$.
25. If plots measuring a catastrophic loss were somehow excluded from the study, they would have been done so a priori or post priori. A mechanism for a priori exclusion would be that forest vulnerable to catastrophes is selected against when plots are established, but it is difficult to see what criteria could be used to make such an assessment. For example, while multiple tree-falls covering large areas do occasionally occur, where they will occur is unknowable. Moreover, any such tendency may select against young stands obviously recovering from disturbances (for example, gaps regenerating after local flooding) and bias our results instead to the parts of the landscape gaining C less rapidly. A mechanism for post priori exclusion would be that plots suffering catastrophic losses are abandoned and not reported. However, we are not aware of any cases of abandoning tropical forest plots after catastrophic loss, and monitoring the impacts of such natural catastrophic events would presumably be of extra scientific value [see also (*9*)].
26. As an example, we take the BIONTE study area in central Amazonia where diameter/biomass relationships have been derived for individual tree species. In the BIONTE study plots of 3 ha by 1 ha (site 8), mean biomass is 353 t ha^{-1}. Biomass of the five largest trees was 17.2, 13.0, 9.4, 8.0, and 7.8 t. Thus, the loss of one of these large trees would only represent a loss of 1.6, 1.2, 0.9, 0.8, and 0.8% of the total inventoried biomass (equivalent to 4.9 to 2.2%, respectively, of total biomass in 1 ha). Although some trees are very long-lived [J. Q. Chambers, N. Higuchi, J. P. Schimel, *Nature* **391**, 135 (1998)], the dynamics of the much more numerous smaller trees are more important. In the BIONTE example, the gain of biomass in the 3 ha by 1 ha study between 1980 and 1997 was 90.5 t, which represents the equivalent of 5.3 times the biomass of the single largest tree and is spread throughout the study area. On a wider scale, many of the Neotropical plots have recently experienced very high mortality rates and rapid recruitment of small trees [O. L. Phillips, P. Hall, A. H. Gentry, S. A. Sawyer, R. Vásquez, *Proc. Natl. Acad. Sci. U.S.A.* **91**, 2805 (1994); O. L. Phillips, *Environ. Conserv.* **23**, 235 (1996); O. L. Phillips, P. Hall, S. Sawyer, R. Vásquez, *Oikos* **79**, 183 (1997)], which indicates that Neotropical forest dynamics are not dominated by the behavior of a few giant, slow-growing trees.
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34. We assumed that: (i) 48% of biomass is in the form of C (based on burning experiments near Manaus, central Amazonia [J. A. Carvalho Jr., J. M. Santos, J. C. Santos, M. M. Leitão, N. Higuchi, *Atmos. Environ.* **29**, 2301 (1995); J. A. Carvalho Jr., N. Higuchi, T. M. Araujo, J. C. Santos, *J. Geophys. Res.* **103**, 13195 (1998)]); (ii) that the ratio of aboveground biomass to root biomass is 3:1 (the average value of three studies in Brazilian Amazonia [P. Fearnside, *Emissão e Sequestro de CO_2* (Companha Vale do Rio Doce, Rio de Janeiro, 1994), pp. 95–124]), consistent with a global analysis of root biomass allocation [M. A. Cairns, S. Brown, E. Helmer, G. Baumgardner, *Oecologia* **111**, 1 (1997)]; and (iii) that root biomass increased in proportion to aboveground biomass. We ignored C stocks in fine litter, dead wood, and soil, which may also have changed.
35. Although PSP data address the problem of spatial variability that can limit extrapolation of eddy covariance studies, they clearly cannot assess the behavior of necromass and belowground C pools, which might be expected to increase together with biomass. A combination of eddy covariance and biomass studies may provide a useful tool in the future to examine belowground processes.
36. The "missing" sink was recently estimated at ~1.4 Gt [D. S. Schimel, *Global Change Biol.* **1**, 77 (1995)]. By comparison, deforestation in Brazilian Amazonia was estimated to yield a net C emission of 0.34 Gt in 1990 [P. M. Fearnside, in *Biomass Burning in South America, Southeast Asia, and Temperate and Boreal Ecosystems, and the Oil Fires of Kuwait*, J. S. Levine, Ed. (MIT Press, Cambridge, MA, 1996), pp. 606–617]. Deforestation in the whole Neotropics was estimated to yield 0.6 ± 0.3 Gt C annually between 1980 and 1990 [R. A. Houghton, in *Forest Ecosystems, Forest Management and the Global Carbon Cycle*, M. G. Apps and D. T. Price, Eds., *NATO ASI Ser. I Global Environ. Change*, vol. 40 (Springer-Verlag, Heidelberg, Germany, 1996)].
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A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models

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Atmospheric carbon dioxide increased at a rate of 2.8 petagrams of carbon per year (Pg C year^{-1}) during 1988 to 1992 (1 Pg = 10^{15} grams). Given estimates of fossil carbon dioxide emissions, and net oceanic uptake, this implies a global terrestrial uptake of 1.0 to 2.2 Pg C year^{-1}. The spatial distribution of the terrestrial carbon dioxide uptake is estimated by means of the observed spatial patterns of the greatly increased atmospheric carbon dioxide data set available from 1988 onward, together with two atmospheric transport models, two estimates of the sea-air flux, and an estimate of the spatial distribution of fossil carbon dioxide emissions. North America is the best constrained continent, with a mean uptake of 1.7 ± 0.5 Pg C year^{-1}, mostly south of 51 degrees north. Eurasia–North Africa is relatively weakly constrained, with a mean uptake of 0.1 ± 0.6 Pg C year^{-1}. The rest of the world's land surface is poorly constrained, with a mean source of 0.2 ± 0.9 Pg C year^{-1}.

A number of carbon cycle studies conducted in the last decade have indicated that the oceans and terrestrial ecosystems in the Northern Hemisphere absorb atmospheric CO_2 at a rate of about 3 Pg C year^{-1} (*1–3*). Atmospheric CO_2 concentrations in the Northern Hemisphere are about 3 parts per million (ppm, mole fraction in dry air) greater than those in the Southern Hemisphere. Fossil CO_2 is released predominantly at northern latitudes (Table 1), which should result in a north-to-south decrease of 4 to 5 ppm in the concentration of atmospheric CO_2 (*4*). A Northern Hemisphere sink is implied because the observed gradient is smaller than this. The original studies disagreed on whether the sink was predominantly oceanic (*1*) or terrestrial (*2*). Recent studies with atmospheric $^{13}C/^{12}C$ ratios (*5*) and oxygen concentrations (*6*) concluded that the sink is caused primarily by terrestrial biosphere uptake. Other studies demonstrated increased activity of sufficient magnitude by the terrestrial biosphere in northern latitudes: a longer growing season observed in satellite measurements of surface color (*7*) and an increase over time of the amplitude of the annual cycle of atmospheric CO_2 concentrations caused by terrestrial vegetation (*8*).

The partitioning of the Northern Hemisphere terrestrial CO_2 sources and sinks between Eurasia and North America may be estimated by using the west-to-east gradient of atmospheric CO_2 across the continents. The west-east signal is much smaller and more difficult to detect than the north-south signal for two reasons. First, the CO_2 distribution is smoothed more by the relatively rapid zonal atmospheric transport than by the slower meridional transport (weeks instead of ~1 year for interhemispheric exchange). Sec-

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ond, atmospheric sampling stations have traditionally been located primarily offshore, away from the largest terrestrial signals to avoid the complexities associated with continental atmospheric boundary layers, the diurnal character of photosynthesis, local fossil fuel emissions, and topography (Fig. 1).

To provide improved estimates of net annual terrestrial sources and sinks, we have developed an inverse model. Let $O(\mathbf{x})$ be the annual-average spatial pattern of atmospheric CO_2 caused by atmospheric transport acting on the sea-air CO_2 flux, and $F(\mathbf{x})$ and $R(\mathbf{x})$ be the corresponding annual-average spatial patterns associated with fossil fuel emissions and the seasonal rectification, respectively (where $\mathbf{x}$ is the spatial coordinate vector). Seasonal rectification results from the correlation between the seasonality of vertical mixing in the atmosphere and the seasonality of photosynthesis and respiration in the land biosphere, which causes gradients in the annual mean CO_2 concentration even when the terrestrial biosphere has no net annual emissions (*9*). Assuming a terrestrial biosphere with no net emissions, the expected annual average spatial pattern of atmospheric CO_2 is $O(\mathbf{x}) + F(\mathbf{x}) + R(\mathbf{x})$. We use the difference between this expected spatial pattern and the observed annual average concentrations of atmospheric CO_2 at sampling stations [$S(\mathbf{x}_j)$ for a station located at $\mathbf{x}_j$] to estimate the magnitude and spatial distribution of terrestrial uptake.

We divide the land surface into N regions and let $b_i(\mathbf{x})$ be the global spatial pattern of atmospheric CO_2 caused by atmospheric transport acting on a standard annual terrestrial uptake of 1 Pg C within the i^{th} region. Then, the total spatial pattern caused by nonzero terrestrial uptake is

$$B(\mathbf{x})=\sum_{i=1}^{N}\alpha_i b_i(\mathbf{x}) \qquad (1)$$

where α_i is the magnitude in Pg C year^{-1} of terrestrial uptake in the i^{th} region, and is estimated by linear regression (*10*).

We used two separate atmospheric transport models of the Geophysical Fluid Dynamics Laboratory (GFDL) to calculate the expected spatial pattern of atmospheric CO_2. A previous model comparison study showed significant differences in predictions of the fossil CO_2 distribution and rectification effect (*4*). The use of two different models gives us some measure of the sensitivity of the results to differences in the transport model. The Global Chemical Transport Model (GCTM) uses winds generated previously by an atmospheric general circulation model (*11*, *12*). In contrast, the SKYHI model (*12*, *13*) calculates tracer transport at the same time it calculates the winds and subgrid-scale mixing.

To calculate the $O(\mathbf{x})$ function, we used two different estimates of the global spatiotemporal distribution of net sea-air CO_2 flux. OBM is an annual mean sea-air flux from a global ocean biogeochemistry model (*14*). T97 is a seasonally resolved sea-air flux field based on estimates from the more than 2.1 million measurements of the sea-air difference of CO_2 partial pressure (pCO_2) gathered over the last three decades and interpolated by using annual mean ocean currents from OBM (*15*, *16*). Pacific equatorial (10°N to 10°S) observations made during El Niño periods were excluded from the estimate. The data are normalized to 1990. The total sea-air CO_2 flux is larger in OBM than T97 (Table 1). A comparison of model simulations with observations of $\Delta^{14}C$ in the ocean favors the larger uptake of OBM (*17*).

The two atmospheric models and two patterns of sea-air CO_2 flux gave us four possible combinations. To calculate in each case, we ran the atmospheric model with the prescribed pattern of sea-air flux for five annual cycles until the annual average spatial distribution of atmospheric CO_2 reached a steady state.

To calculate $O(\mathbf{x})$, we used data on national fossil fuel consumption distributed with the same spatial distribution as population density (*18*). Using this pattern of release at the surface, we ran each atmospheric model to its steady state as above.

Finally, to calculate $R(\mathbf{x})$ and the $b_i(\mathbf{x})$, a

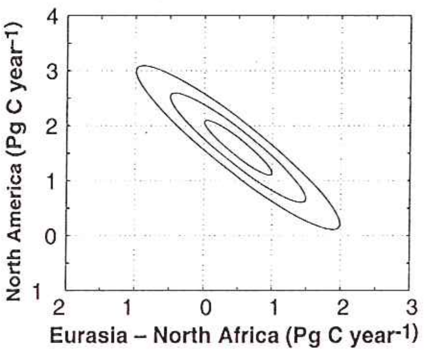

Fig. 2. Inversion uncertainties for North American terrestrial uptake versus Eurasia–North African terrestrial uptake. Ellipses of 1, 2, and 3 SDs are shown.

Table 1. Regional distribution of fossil CO_2 emissions and sea-air fluxes for 1990. T97 and OBM are two different air-sea flux estimates (see text).

Region	Fossil emissions (Pg C year^{-1})
North America (>15°N)	1.6
Eurasia and North Africa (>24°N)	3.6
Tropics and Southern Hemisphere	0.7
Total	5.9

	Ocean uptake (Pg C year^{-1})	
	T97	OBM
North Atlantic (>15°N)	0.55	0.51
North Pacific (>15°N)	0.29	0.70
Tropics and Southern Hemisphere	0.27	1.04
Total	1.11	2.25

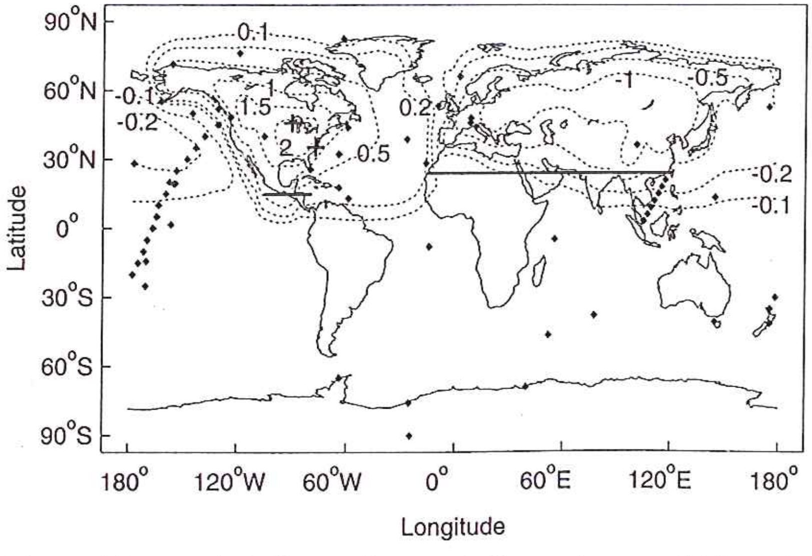

Fig. 1. A map of the atmospheric CO_2 sampling network. Sites are shown as solid diamonds. (The Globalview labels for the Northern Hemisphere stations are given in the legend of Fig. 3). The tall tower sites are shown as crosses. The thick horizontal lines divide the land surfaces into three regions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

model of the terrestrial biosphere is required. We chose the Carnegie-Ames-Stanford Approach (CASA) model (*19*), because it predicts ecosystem fluxes of CO_2 with a relatively straightforward extrapolation of global satellite imagery (normalized difference vegetation index or NDVI measurements on a 1° grid). We calculated $R(\mathbf{x})$ by running each atmospheric model with surface fluxes from a version of the CASA model (again until a steady state spatial pattern was achieved). To calculate $b_i(\mathbf{x})$, we ran the atmospheric model with no sources or sinks of CO_2 except net primary production (NPP) from the CASA model in only the i^{th} region. This NPP was first rescaled until the annual total was 1 Pg C. Thus, the spatiotemporal distribution of estimated carbon sinks within each terrestrial region is assumed to be proportional to the distribution of NPP, but this assumption has little impact on the results (see below).

The atmospheric CO_2 data we used cover the 1988 to 1992 period at a subset of 63 sampling stations (*20*) taken from the GLOBALVIEW database (*21*) compiled with methods as described by Masarie and Tans (*22*) (Fig. 1). Before 1988 there were fewer sampling stations; a separate study indicates that even with optimal placement, which the present data set does not have, a minimum of about 10 stations per region is necessary to obtain estimates with useful accuracy (*23*).

We first defined three regions, North America north of 15°N, Eurasia–North Africa north of 24°N, and all other land to the south (Fig. 1). Subsequently, North America was separated into temperate and boreal zones at approximately the evergreen–broadleaf ecotone (51°N). Additional divisions lead to prohibitively large estimation errors. In particular, there are insufficient atmospheric stations in the Southern Hemisphere to separate Africa from South America.

North America is constrained by the atmospheric observations on three sides of the continent (Fig. 1); a large North American terrestrial uptake is estimated in all four combinations of atmospheric models with sea-air CO_2 flux data (Table 2). Most of the North American terrestrial uptake (70 to 100%) is estimated to be in the broadleaf region south of 51°N. If the North American terrestrial uptake were zero (that is, all of the Northern Hemisphere's net terrestrial uptake were in Eurasia), the models would predict an average increase of atmospheric CO_2 of more than 0.3 ppm from stations located between 10°N and 60°N in the North Pacific to those in the North Atlantic. A North American terrestrial sink is implied by the data because the observed gradient shows a decrease from North Pacific to North Atlantic of about 0.3 ppm.

We estimated standard deviations for the estimates of terrestrial uptake by propagating independent, identically distributed Gaussian station errors (Table 2). The ellipses in Fig. 2 suggest that the total Northern Hemisphere sink is well constrained, and that the partitioning between North America and Eurasia–North Africa is more weakly constrained. However, the terrestrial carbon sink in North America is sufficiently large to be detected with the present observational and model constraints.

None of these error estimates include systematic errors such as differences between GCTM and SKYHI and between T97 and OBM. We use the differences between estimates from the four models (Table 2) as an admittedly limited assessment of the magnitude of systematic errors. The range of estimates produced by the differences between the models is small for North American uptake and intermediate for Eurasian uptake. Estimates of Eurasia–North African terrestrial uptake obtained with SKYHI are 0.7 to 0.9 Pg C year^{-1} lower than those obtained with GCTM. SKYHI has a more rapid vertical mixing than GCTM and predicts lower fossil CO_2 at stations in the mid-latitude Northern Hemisphere, which implies a lower terrestrial uptake in the region.

The systematic errors are especially large for estimates of the terrestrial uptake in the tropics and Southern Hemisphere, as evidenced by the large differences among the estimates shown in Table 2. The wide range of 2.0 Pg C year^{-1} in these estimates is caused by a combination of factors. Differences between OBM and T97 account for 1.3 Pg C year^{-1} (Table 2). Differences between SKYHI and GCTM account for 0.7 Pg C year^{-1}.

An alternative four-region inversion, with only one region in North America but two in Eurasia–North Africa, yields marginal evidence of a weak uptake in boreal Eurasia (0.6 ± 0.4 Pg C year^{-1}) with a more uncertain, but generally compensating source in temperate Eurasia (−0.5 ± 0.7 Pg C year^{-1}). However, five-region inversions (with separate temperate and boreal regions in both North America and Eurasia–North Africa) were unstable, with standard errors of estimates as large as 1.4 Pg C year^{-1}. The only stable regions were temperate and boreal North America and the union of temperate and boreal Eurasia–North Africa, for which terrestrial uptake estimates and errors similar to those in Table 2 were obtained.

Detection of the terrestrial CO_2 uptake in North America and in Eurasia can be improved

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.

with atmospheric measurements within or near the continents. If the North American uptake were zero, the CO_2 mixing ratios over eastern North America should increase by over 2 ppm (Fig. 1), which would make that the best place to detect a source or sink proportional to NPP. Data are available from two extremely tall towers (>400 m) within this region (crosses in Fig. 1) for a period later than the 1988 to 1992 interval considered here. Analyzed with a completely different method, these data are consistent with the existence of a large sink in North America (*24*).

A detailed summary of the present data that constrain the North American sink (Fig. 3) illustrates how near the limit of detection the signal is. The fit of the model to the observations in the optimal case is better than 0.5 ppm at most locations in both the Pacific and Atlantic. Zeroing out the North American sink lowers the Pacific model predictions and raises the Atlantic, thereby reversing the west-to-east gradient from −0.3 to +0.3 ppm (Fig. 3; note particularly that the Atlantic predictions go from being relatively well centered around the observations to having five stations well above the observations). Zeroing out Eurasia raises the model predictions in the Pacific and lowers them in the Atlantic.

We tested the sensitivity of the solutions to individual stations by removing stations one at a time. In all cases the removal of a station had an impact of ≤ 0.3 Pg C year^{-1}, with most being near zero. The exclusion of Sable Island (44°N60°W) from the data set (*20*) does have a substantial impact on the inversion results. Including it in the GCTM-T97 and -OBM inversions reduces the North American terrestrial uptake by 0.4 to 0.5 Pg C year^{-1} and shifts it to Eurasia–North Africa.

The estimate of North American terrestrial uptake was found to be insensitive to large changes in the North Pacific uptake, and only weakly related to the Southern Ocean (south of 54°S) uptake. In contrast, for an incremental change in the temperate North Atlantic sink, the estimate of North American terrestrial uptake changes by ~1.5 times as much in the opposite direction. However, the temperate North Atlantic sink had to be increased by about a factor of 5, from 0.3 to 1.4 Pg C year^{-1}, to eliminate the North American sink (*25*).

A large North American terrestrial uptake was estimated consistently for a range of spatiotemporal patterns assumed for the terrestrial uptake (*26*), because subcontinental terrestrial signals are sufficiently smoothed at most of the air-sampling stations (Fig. 1).

Suppose that our mean estimate of the North American terrestrial carbon sink were distributed uniformly over the forest region south of 51°N (Table 2) (*27*); then, the per unit area forest uptake would be 3 to 4 t C ha^{-1} year^{-1}. This is in the uppermost range of some independent measurements at local sites (*28*, *29*). A lower estimate on the order of 1 Pg C year^{-1} for the North American terrestrial uptake, which is near the lower error bound of 1 SD (Fig. 2), would be in better agreement with the local measurements. However, even our low estimate is much larger than the 0.2 to 0.3 Pg C year^{-1} uptake estimated on the basis of forest inventory data for North American forests (*30*, *31*), which did not take full account of carbon storage in soils, wetlands, and lakes (*32*).

The terrestrial uptake in North America is at least partly due to regrowth on abandoned farmland and previously logged forests (*30*, *31*). Numerous field and laboratory studies have suggested that terrestrial uptake is currently enhanced by anthropogenic nitrogen deposition [0.2 to 2.0 Pg C year^{-1} globally, with much of this in the Northern Hemisphere (*33*, *34*)], CO_2 fertilization [0.5 to 2.0 Pg C year^{-1} globally, with most of this in the tropics (*33*)], and global warming [mostly in the north temperate zone (*8*, *35*)]. On the other hand, warming might also have reduced terrestrial uptake by enhancing decomposition (*29*, *36*).

Although the inversion results indicate that the North American terrestrial uptake is large enough to be detected with current data and model constraints, its magnitude remains uncertain and its cause unknown. Thus, the immediate implication of our results is the need for additional constraints of four kinds: (i) intensive atmospheric sampling and ecological field studies to indentify the location and cause of North American terrestrial CO_2 uptake; (ii) new atmospheric measurements to constrain estimates for Eurasia, South America, Africa, and Australia; (iii) studies to better characterize oceanic CO_2 uptake, particularly in the Southern Hemisphere; and (iv) reduced uncertainty in atmospheric transport modeling.

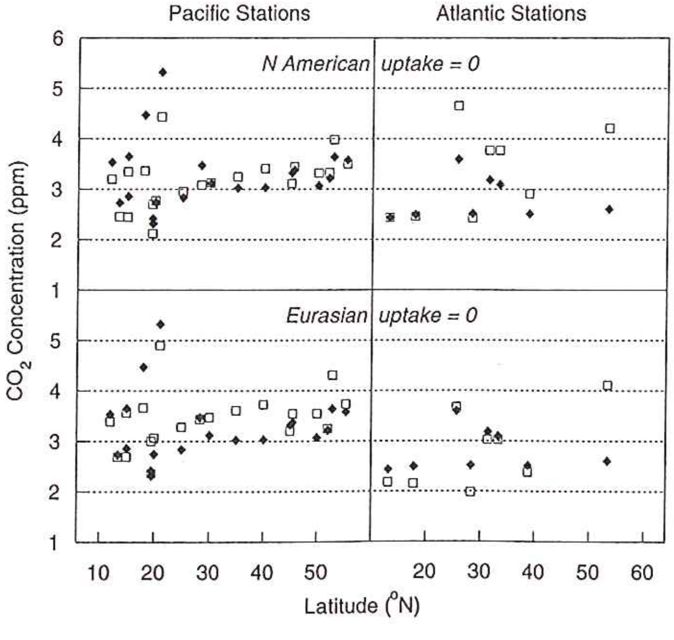

Fig. 3. Comparison of model-predicted atmospheric CO_2 concentrations (□) with observations (1988—1992 average) (◆) at Pacific and Atlantic sampling locations between 10° to 60°N. Model results are shown for GCTM with T97 sea-air fluxes, and with North American terrestrial uptake set to zero (that is, all Northern Hemisphere terrestrial uptake placed in Eurasia–North Africa), or Eurasia–North African terrestrial uptake set to zero (that is, all Northern Hemisphere terrestrial uptake placed in North America). Although the Mace Head station (in the Atlantic at 53.3°N) is an outlier in all plots, it has little impact on the inversion estimates because predictions at this station are affected only slightly by zeroing North American or Eurasian uptake. Data are shown for the following locations, with their latitude (°N) and longitude (a negative sign indicates °W and a positive sign indicates °E) in parentheses: AVI (17.75, −64.75), AZR (38.75, −27.08), BME (32.37, −64.65), BMW (32.27. −64.88), CBA (55.20, −162.72), CMO (45.48, −123.97), CSJ (51.93, −131.02), GMI (13.43, 144.78), IZO (28.30, −16.48), KEY (25.67, −80.20), KUM (19.52, −154.82), MHT (53.33, −9.90), MID (28.22, −177.37), RPB (13.17, −59.43), SHM (52.72, 174.10), STP (50.00, −145.00), pocn15 (15.00, −160.00), pocn20 (20.00, −158.00), pocn25 (25.00, −154.00), pocn30 (30.00, −148.00), pocn35 (35.00, −143.00), pocn40 (40.00, − 138.00), pocn45 (45.00, −131.00), scsn12 (12.00, 111.00), scsn15 (15.00, 113.00), scsn18 (18.00, 115.00), and scsn21 (21.00, 117.00).

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$$\chi^2 = \sum_{j=1}^{q} [B(x_j) + O(x_j) + F(x_j) + R(x_j) - S(x_j)]^2 \quad (2)$$

where q is the number of atmospheric sampling stations. In practice, it is convenient to reference all concentrations in the sum of squares to the value at the South Pole, and then solve for the values of α by using singular value decomposition [W. H. Press, B. R. Flannery, S. A. Teukolsky, W. T. Vetterling, *Numerical Recipes* (Cambridge Univ. Press, New York, 1992)] with a mass conservation constraint [G. H. Golub and C. F. V. Loan, *Matrix Computations* (Johns Hopkins Univ. Press, Baltimore, 1990)] that requires the terrestrial biosphere to balance all the other sources minus sinks.
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20. The GLOBALVIEW-CO2 1996 database has a total of 66 stations. Tae-Ahn Peninsula and Westerland were excluded because they are strongly contaminated by local fossil CO_2 sources that are difficult for the coarse resolution models to simulate in sufficient detail. Sable Island was excluded because it appears that the data may have a positive bias (K. Higuchi, personal communication). The following procedures were followed in calculating annual averages of model simulations for comparison with observations. (i) Sampling of models at coastal stations was moved out to sea by one grid cell in order to avoid inadvertent terrestrial contamination resulting from the coarse resolution of the atmospheric general circulation models (GCMs). (ii) All other sampling was done at the nearest grid cell to the station. (iii) Four stations were sampled by wind sectors in order to match as closely as possible the way that the actual sampling is done: Cape Grim, Tasmania (180° to 270°); Cape Meares, Oregon (210° to 330°); Key Biscayne, Florida (30° to 160°); and Mace Head, Ireland (210° to 300°).
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37. This research was carried out as part of the Carbon Modeling Consortium (CMC), which is supported by the Office of Global Programs and Geophysical Fluid Dynamics Laboratory of the NOAA. We acknowledge support from the Department of Energy. Stimulating discussions with our colleagues in the CMC and elsewhere is gratefully acknowledged, with particular appreciation to P. Bakwin, D. Baker, and M. Bender. L. Bruhwiler, R. Hemler, H. Levy, and W. Moxim provided advice on the GCTM and SKYHI simulations, T. Hughes helped access the OBM results, and C. Field provided the CASA simulation results.

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North Atlantic Oscillation Dynamics Recorded in Greenland Ice Cores

C. Appenzeller,* T. F. Stocker, M. Anklin

Carefully selected ice core data from Greenland can be used to reconstruct an annual proxy North Atlantic oscillation (NAO) index. This index for the past 350 years indicates that the NAO is an intermittent climate oscillation with temporally active (coherent) and passive (incoherent) phases. No indication for a single, persistent, multiannual NAO frequency is found. In active phases, most of the energy is located in the frequency band with periods less than about 15 years. In addition, variability on time scales of 80 to 90 years has been observed since the mid-19th century.

The North Atlantic oscillation (NAO) is one of the Northern Hemisphere's major multiannual climate fluctuations and typically is described with an index based on the pressure difference between Iceland and the Azores (*1*). On multiannual time scales, variations in the NAO have a strong impact on North Atlantic and European climate (*2*) and also on the recent surface temperature warming trend in the Northern Hemisphere (*3*). In recent decades the winter index remained predominantly in a positive state, and there is evidence that during this period the variability might have increased (*4*). Analysis of various NAO indices (*5*) showed

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What is the expected post-industrial temperature rise due to this increased greenhouse forcing?

Current radiation (visible + IR) at $\oplus$ surface

$$u_0 = (1.14)(340) = 388 \text{ W/m}^2$$

$$\sigma T^4 = u_0$$

$$\sigma (T + \Delta T)^4 = u_0 + \overset{2 \text{ W/m}^2}{\swarrow}\delta u_0$$

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

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

$$\boxed{\frac{\Delta T}{T} = \frac{1}{4}\left(\frac{\delta u_0}{u_0}\right)}$$

$$\boxed{\Delta T = 0.4^\circ\text{C} \text{ increase — very slight}}$$

Remember — this a globally averaged temperature rise

This calculation ignores all <u>feedback</u> <u>effects</u>.

Is there any evidence of this?

Very difficult to measure.

Day-to-day & week-to-week and year-to-year as well as geographical variability much larger

Non-uniformity of records — thermometers moved — urban heat island effect.

Nevertheless — most analyses now agree — about 0.6°C temp increase globally in past century.

Mt.
Pinatubo
page
9½

The effects so far (280 ppm → 360 ppm CO_2 and $\Delta T < 1°C$) have been so small that they are difficult to measure & detect. The question of interest is — extrapolation to the future.

First thing to note — CO_2 concentration in atmosphere will continue to increase <u>even</u> if <u>we</u> freeze fossil fuel consumption at current rates

Why — because of the slow time scale for oceanic uptake (centuries)

Also ∃ natural climate variations, e.g.

1991 eruption of Mt. Pinatubo, Philippines — spewed aerosols [illegible] & dust into stratosphere — spectacular red sunsets for ~ one year

Caused increased scattering of visible (SW) light from sun — [illegible] measured using satellite

LW − SW gives total radiative forcing

Peak at 4 W/m^2, over 2 W/m^2 for ~ 1 yr.

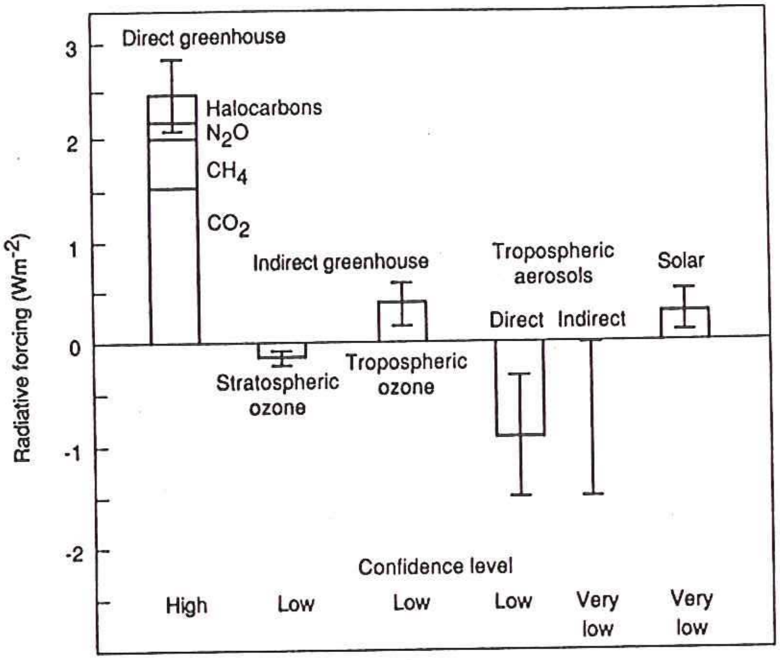
Gave rise to a 0.4 °C [illegible] transient temp decrease — lasted ~ 2 yrs before recovery

Can be seen in Hansen temperature data.
Figure 4.7

El Chichon volcano in 1981 also

Main cause is SO_2 emissions by volcanoes.

Can measure scattering intensity of a laser beam — gives a measure of aerosol content



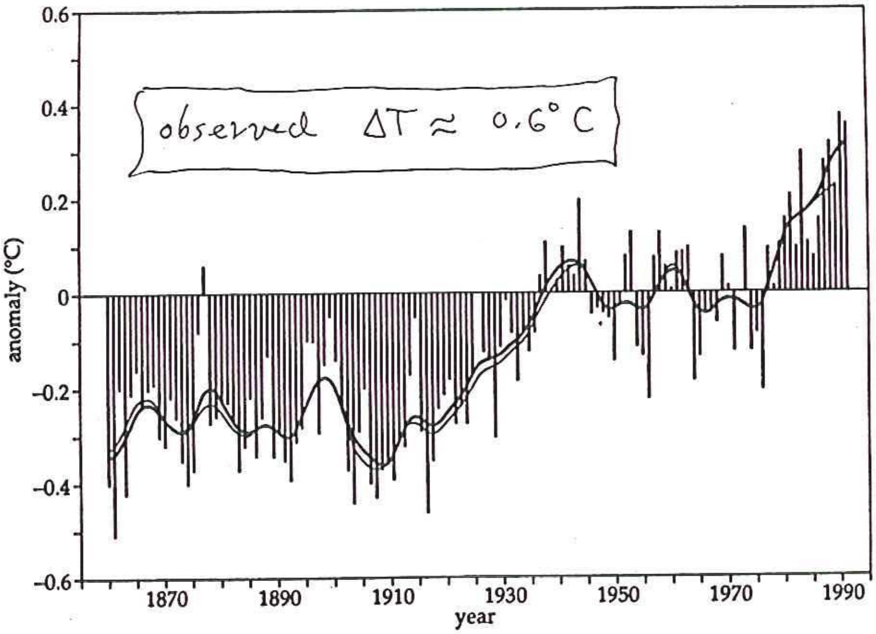
Total anthropogenic radiative forcing

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

Purely radiative temperature increase

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

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



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

But there is considerable natural variability.

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.

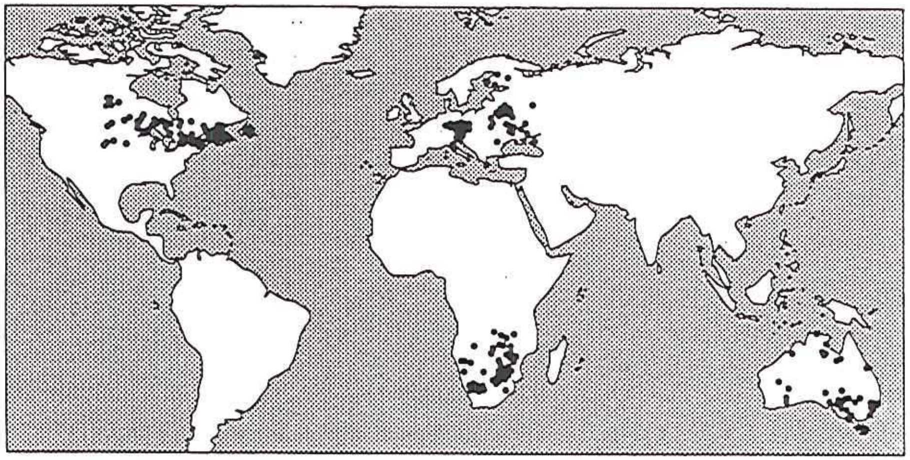


Fig. 1. Locations of 358 boreholes, whose subsurface temperature measurements were analyzed to reconstruct a surface temperature history. There are 116 sites in eastern North America, 98 in central Europe, 86 in southern Africa, and 58 in Australia.

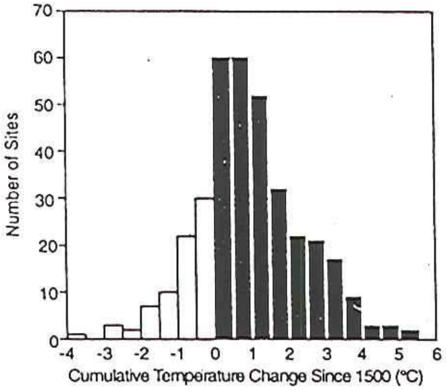


Fig. 2. Histogram of cumulative five-century temperature changes at sites shown in Fig. 1. Black columns indicate net warming and white columns indicate net cooling.

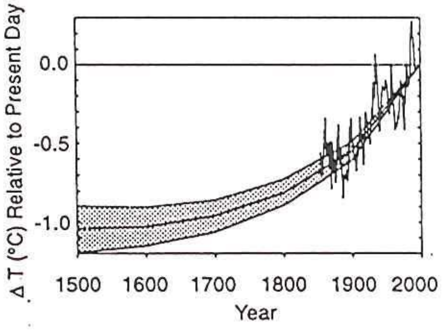
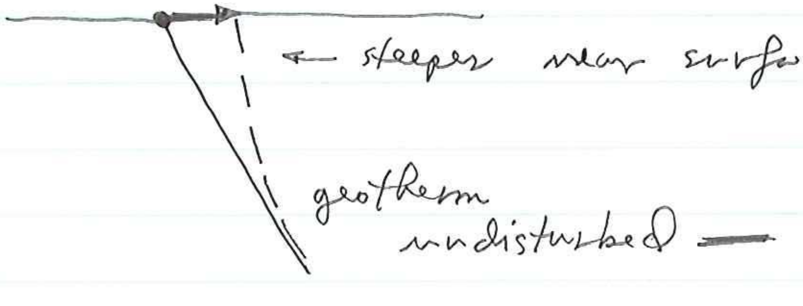


Fig. 3. Composite four-region surface temperature change over the past five centuries, relative to the present, as determined from geothermal data. Shaded areas represent ±1 standard error about the mean history. Superimposed is a smoothed (5-year running average) SAT instrumental record (*10*) representing 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.

Pollack et al. extrapolation into past using heat flow data

Idea is this:



Analyzed ~ 350 boreholes
More sites warmed than cooled

20th century data agrees with instrumental record.

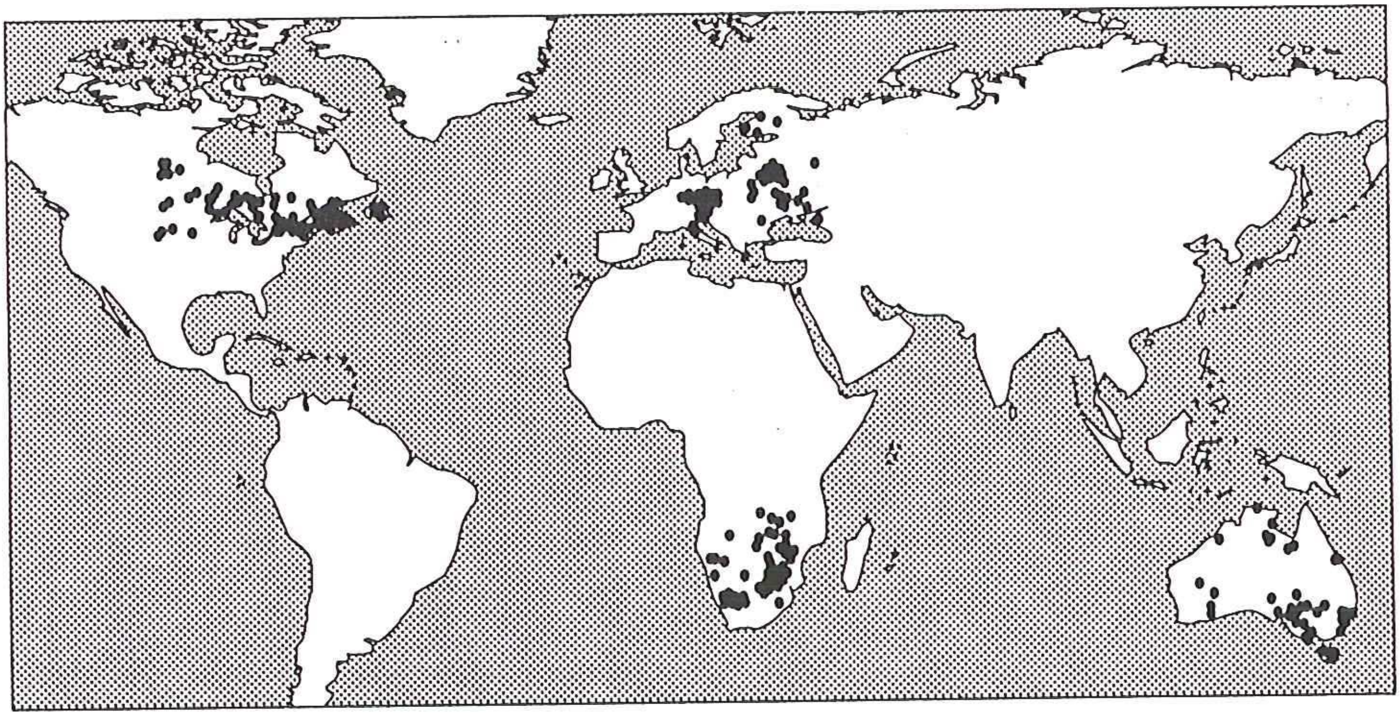
Find a total 1°C warming over past five centuries

Most increase since Industrial Revolution

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.



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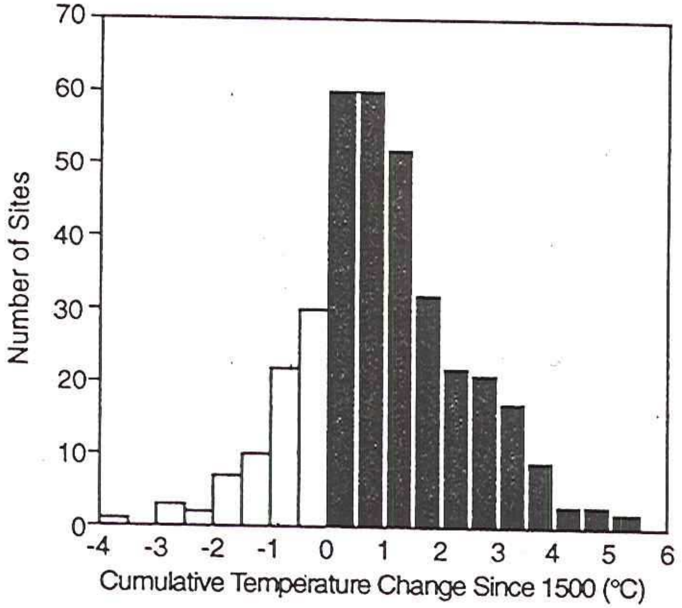

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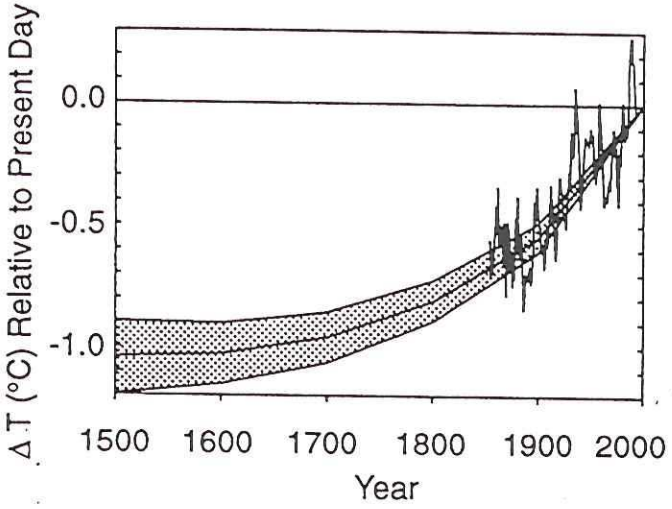

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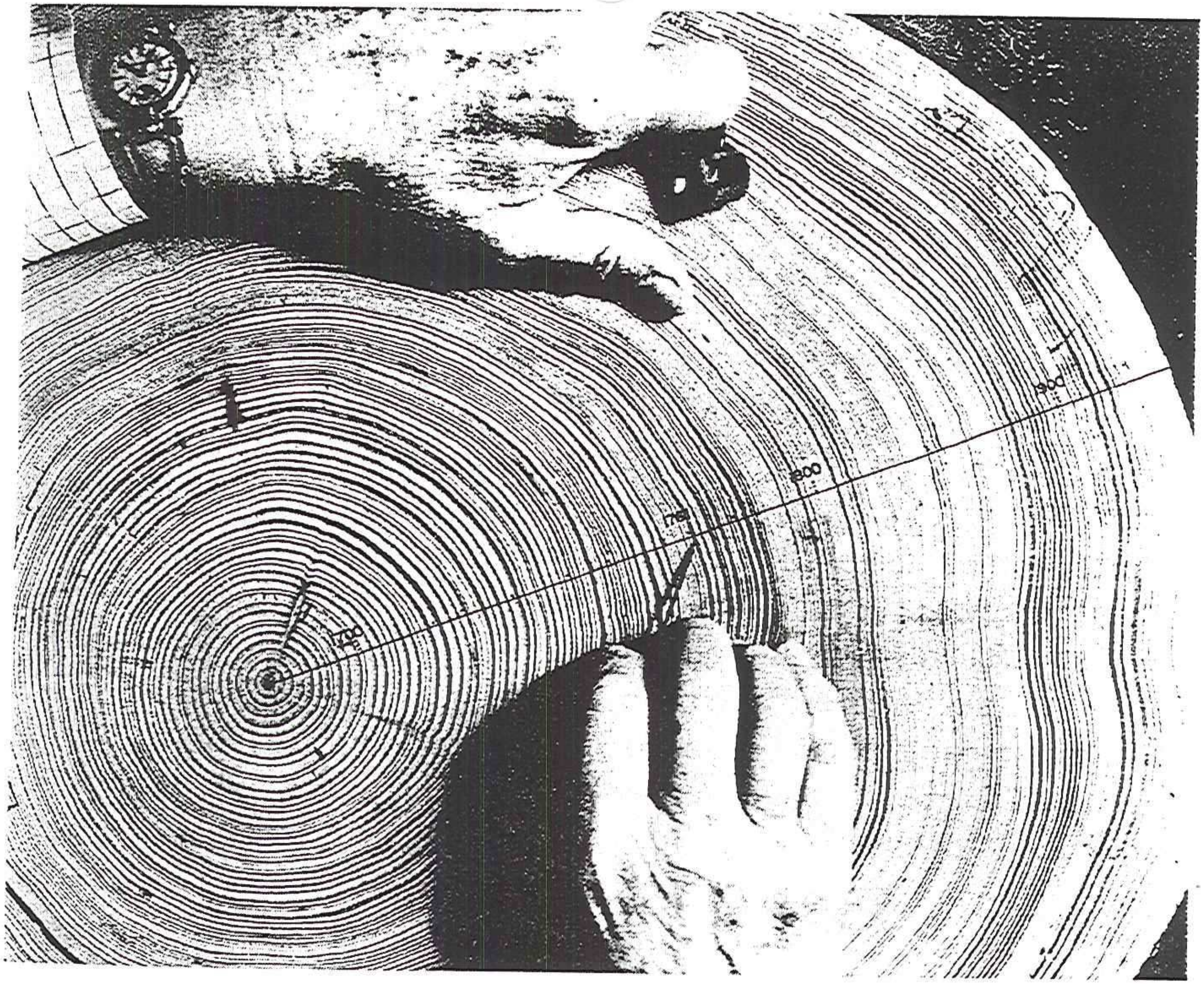
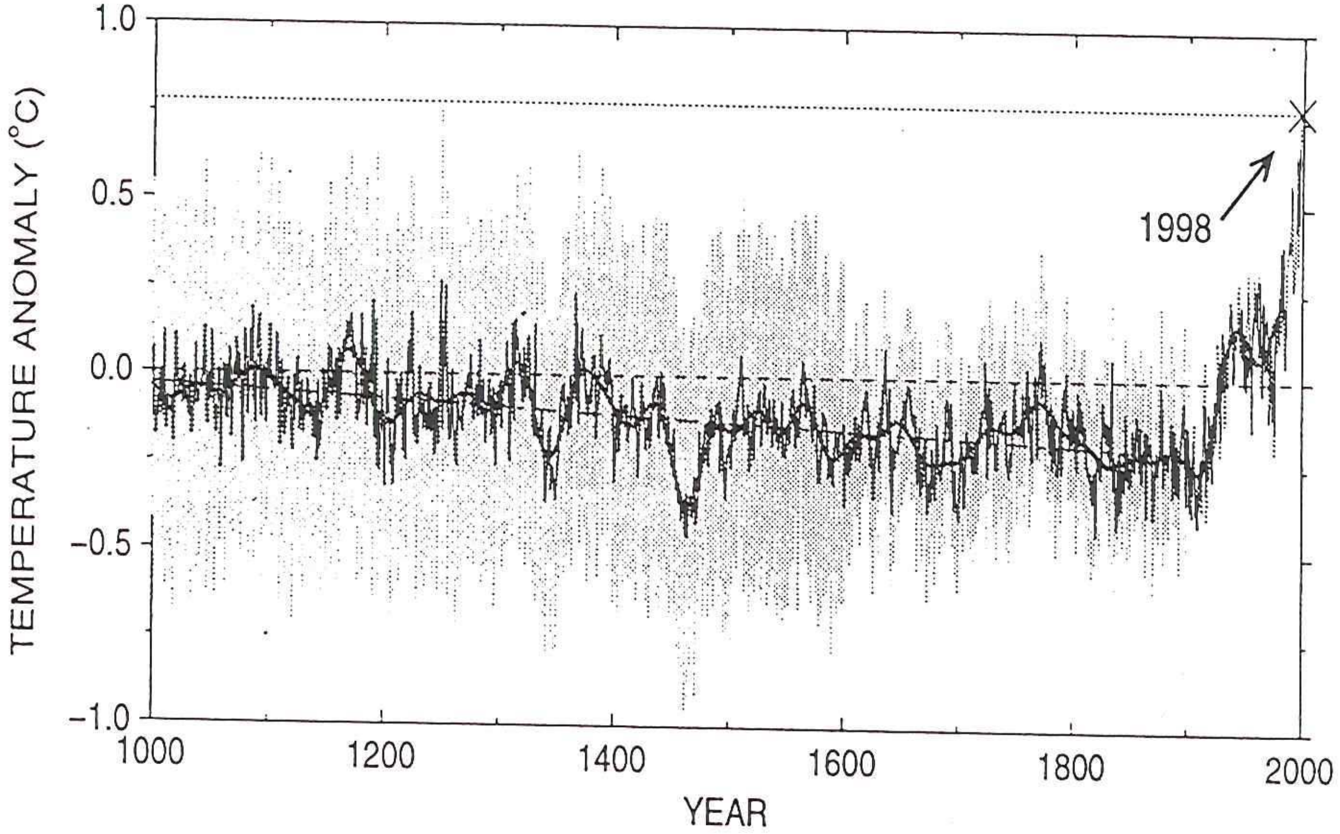


FIGURE 2–1 A cross section of the trunk of a Douglas fir shows the method of dating tree rings *(dendrochronology)*. The annual variability of ring widths in this species provides a record of climate change during the life of the tree. (Photograph courtesy of the Laboratory of Tree-Ring Research, the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


1.0
0.5
0.0
-0.5
-1.0
TEMPERATURE ANOMALY (°C)
1000
1200
1400
1600
1800
2000
YEAR
1998

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 $\sim 2 \times 10^{23}$ 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 $\sim 10^{23}$ 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.

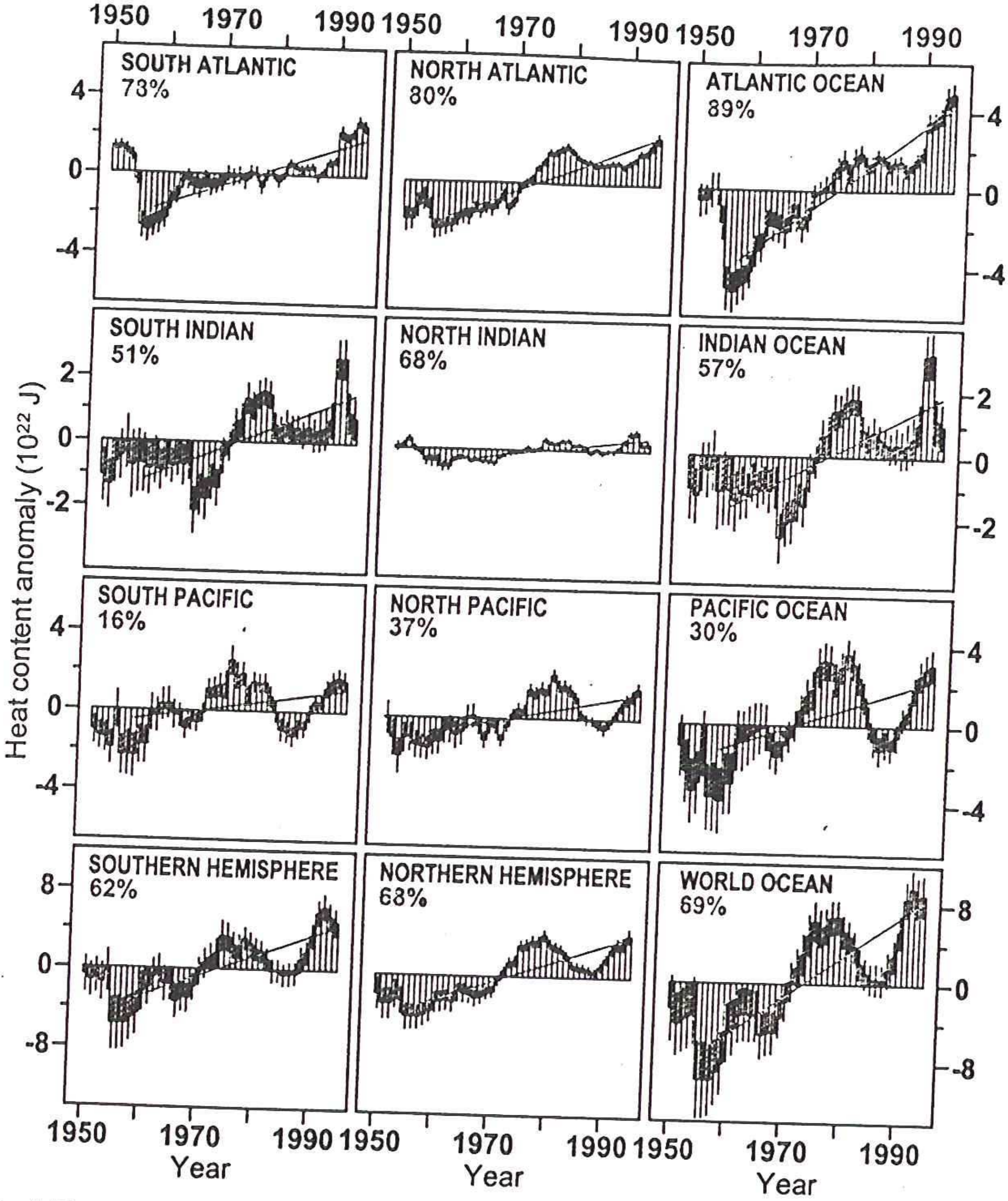


Fig. 4. Time series of 5-year running composites of heat content (10^{22} J) in the upper 3000 m for each major ocean basin. Vertical lines represent ±1 SE of the 5-year mean estimate of heat content. The linear trend is estimated for each time series for the period 1955 to 1996, which corresponds to 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*).

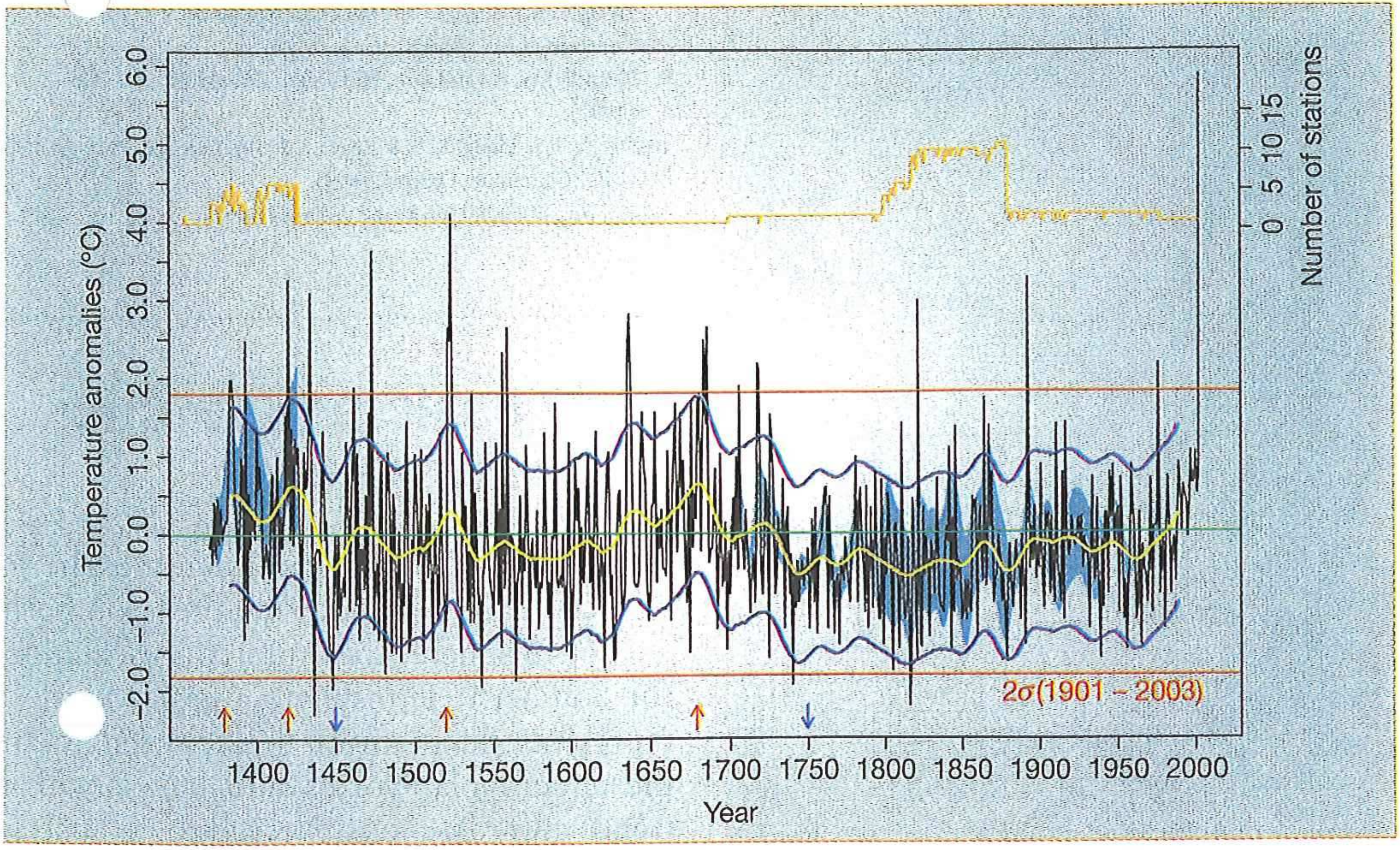


Figure 1 April–August temperature anomalies in Burgundy, France, as reconstructed from grape-harvest dates from 1370 to 2003. Yearly anomalies are in black and the 30-year gaussian filter is in yellow. Confidence intervals due to vineyard differences, with an 11-year smoothing, are shaded in blue; these are estimated from the inter-station variability upper 90th and lower 10th percentiles, and are determined when there are more than three available observations in a year. Orange line (number of stations) represents the number of observed harvest dates for each year, indicating where the confidence intervals are computed. Confidence intervals with two s.e., due to the regression between observed and reconstructed temperature in Dijon, are in purple. These were obtained by regressing the reconstructed temperature with the observed temperature over 1880–2000. Green horizontal (zero) line is determined from the 1960–89 reference period. Red horizontal lines represent the 2σ interval of the reconstructed temperature for the twentieth century (1901–2003). Vertical arrows indicate warm decadal periods (red) above the 90th percentile and the cold trends (blue) under the 10th percentile.

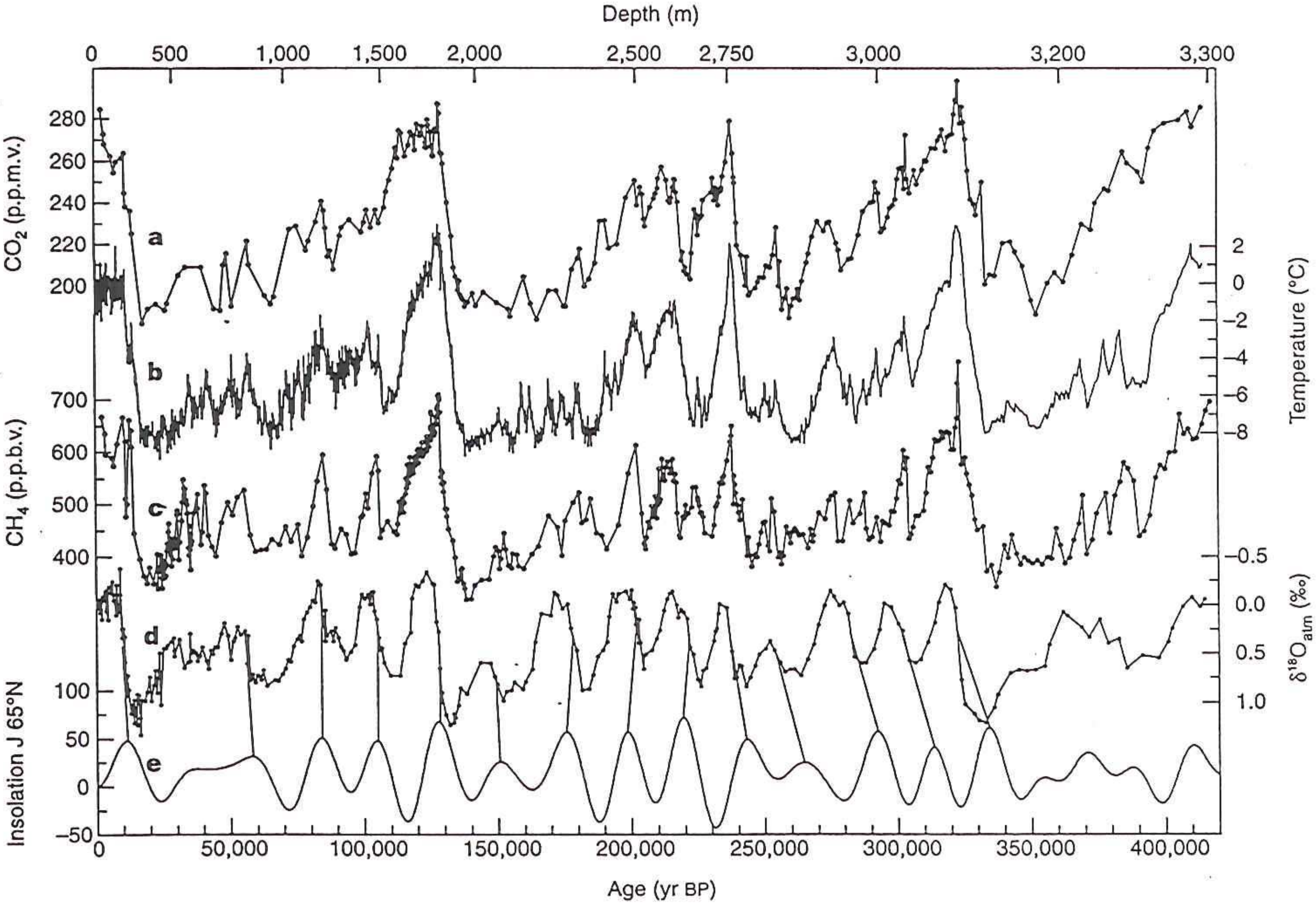


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June 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.

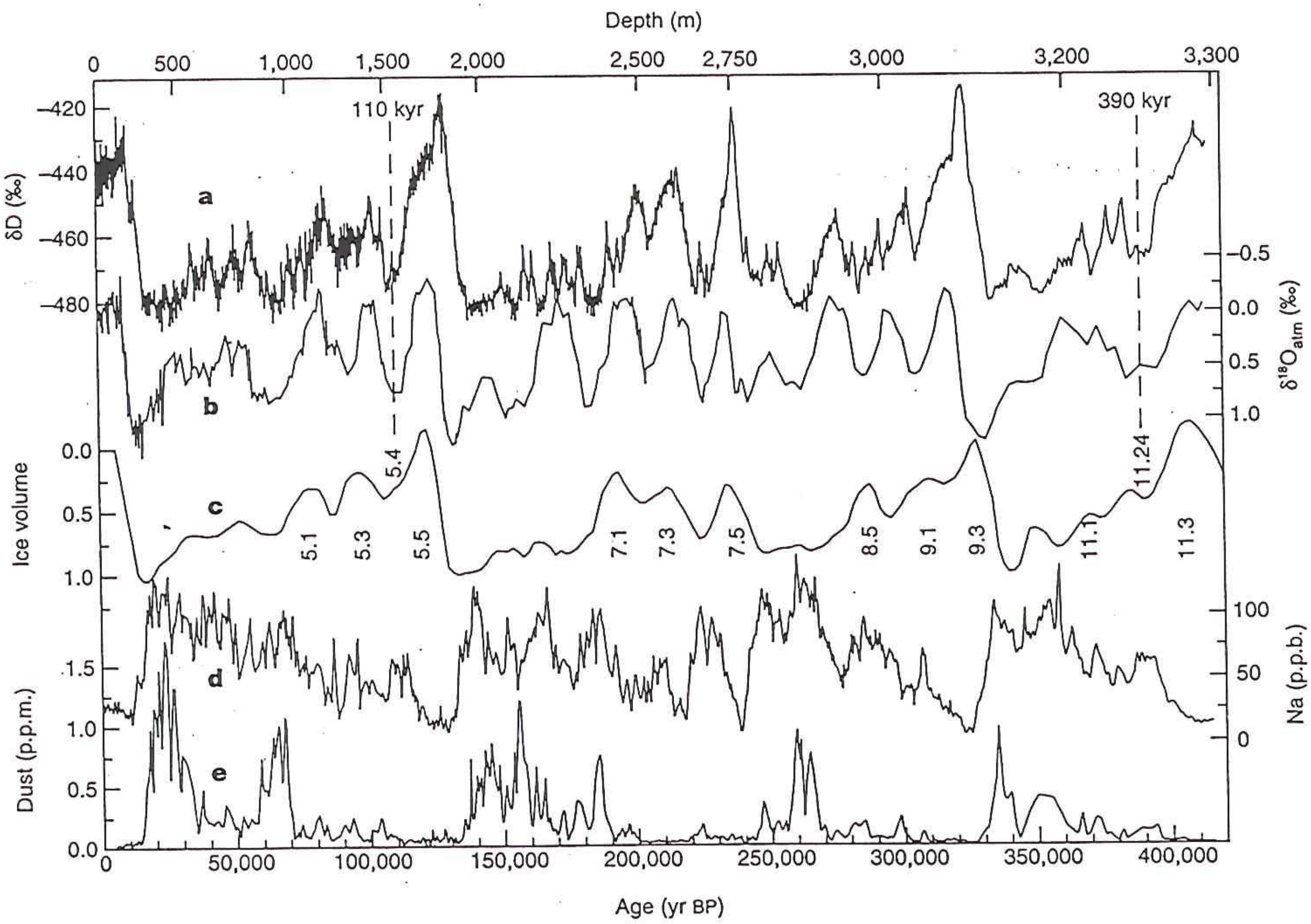


Figure 2 Vostok time series and ice volume. Time series (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis and indication of the two fixed points at 110 and 390 kyr) of: **a**, deuterium profile (from Fig. 1); **b**, $\delta^{18}O_{atm}$ profile obtained 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.

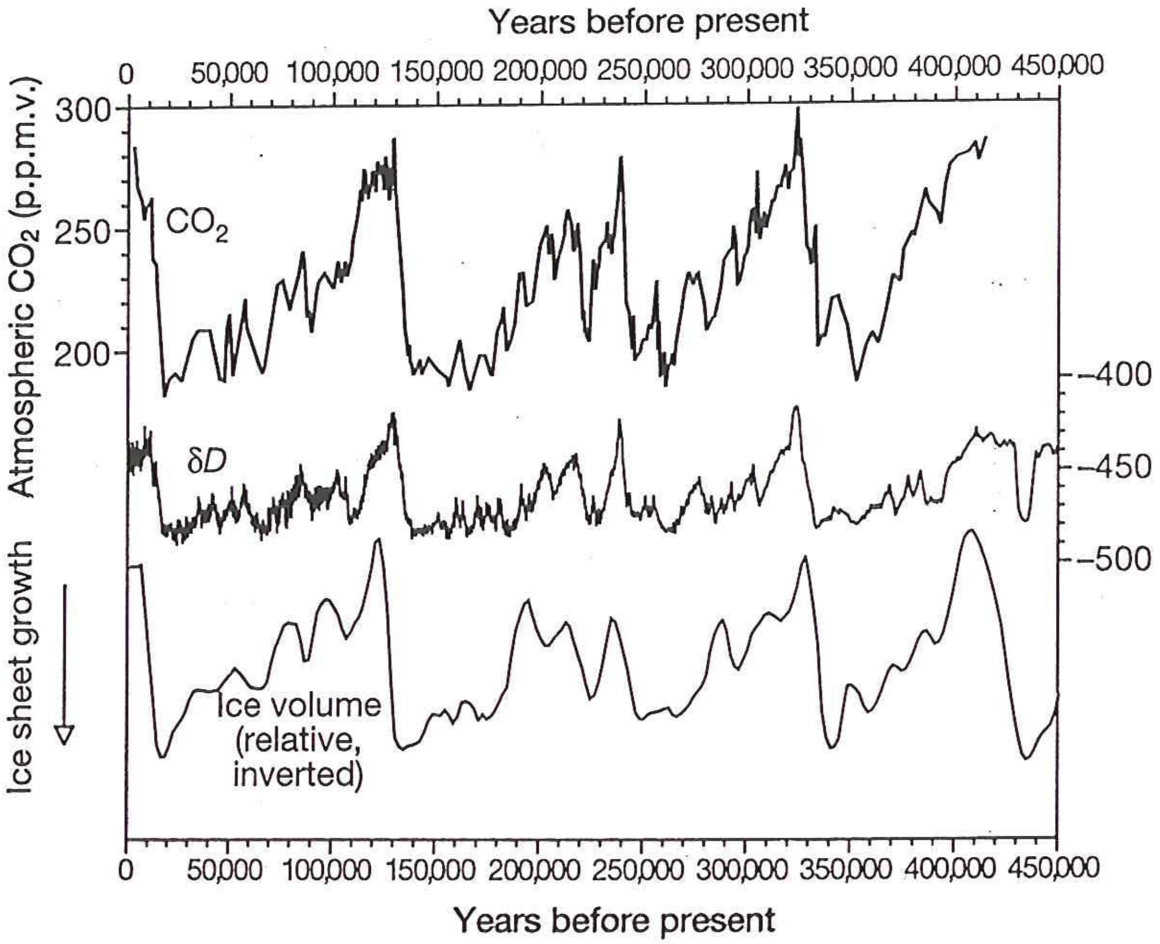


Figure 1 The history of atmospheric CO_2 back to 420 kyr ago as recorded by the gas content in the Vostok ice core from Antarctica[4]. The ratio of deuterium to hydrogen in ice (expressed as the term δD) provides a record of air temperature over Antarctica, with more negative δD values corresponding 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.

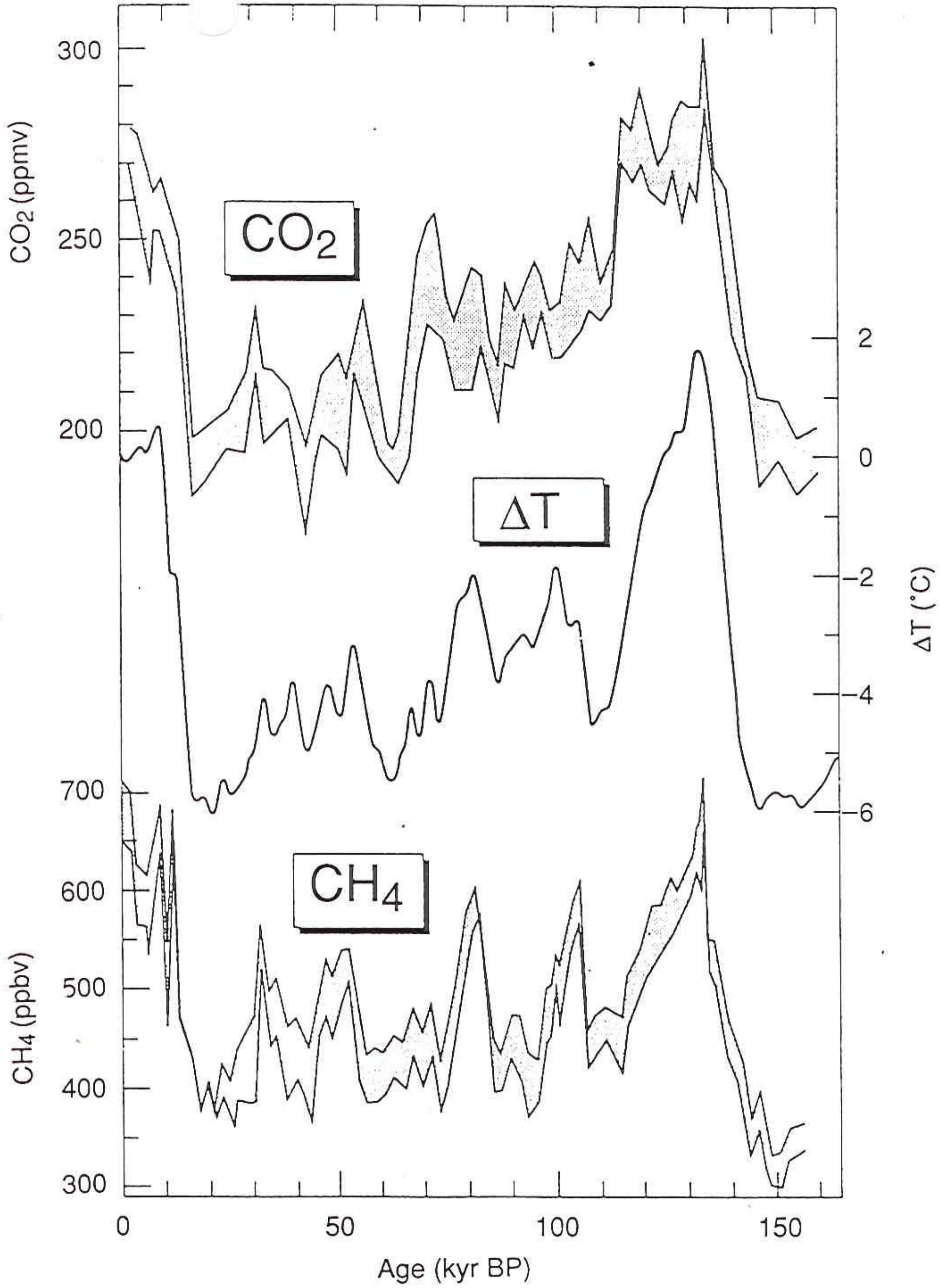


Figure 1.4 Antarctic ice core records of local atmospheric temperature and atmospheric carbon dioxide and methane volume mixing ratios for the past 160,000 years. (Mixing ratios and other units are discussed in the appendix on units of measurement.) Note that for most of the period temperatures were 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.)

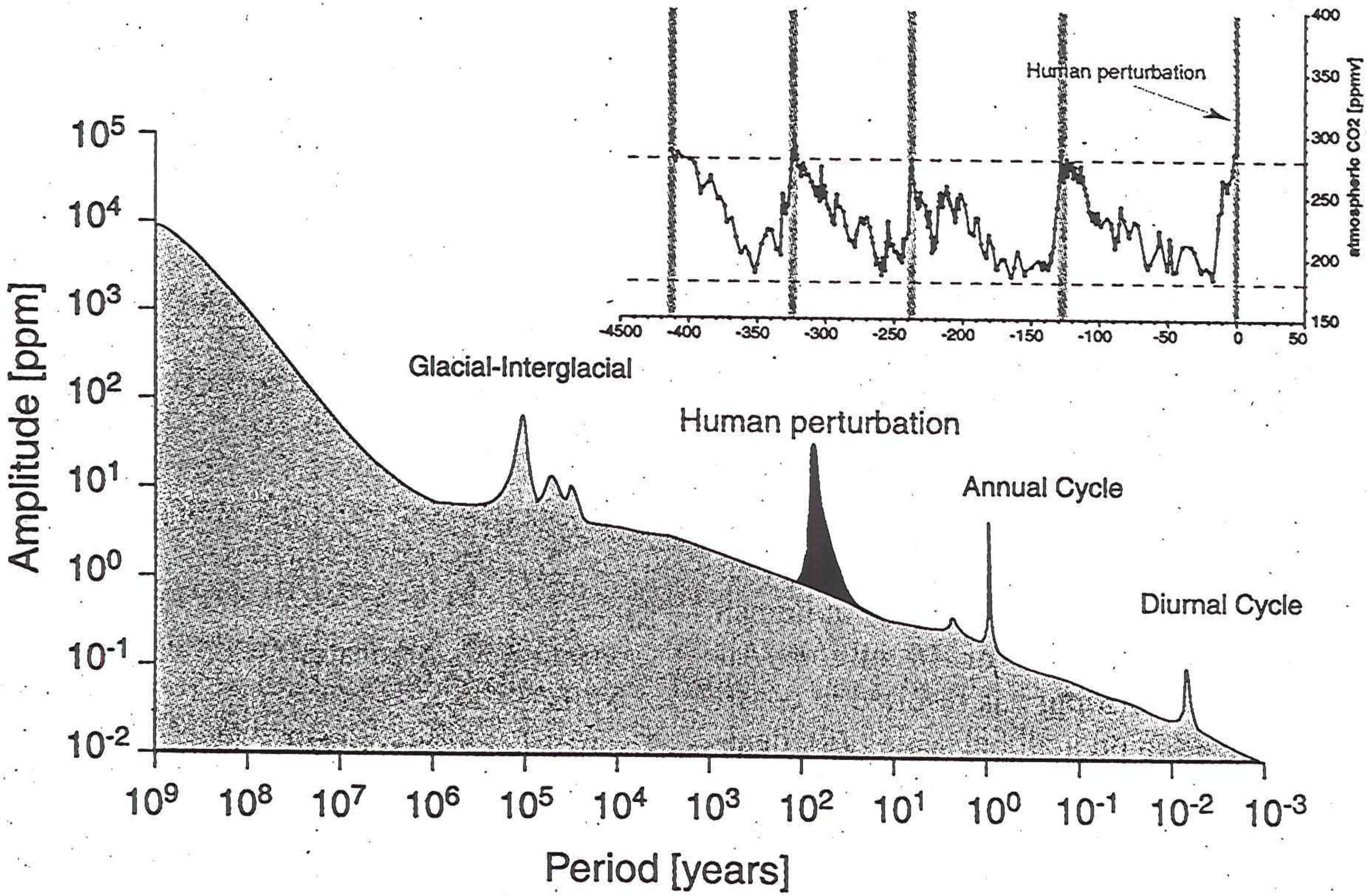


Fig. 2. Schematic variance spectrum for CO_2 over the course of Earth's history. Note the impact of human perturbations on the decade-to-century scale. (**Inset**) Changes in atmospheric CO_2 over the past 420,000 years as recorded in the Vostok ice, showing that both the rapid rate of change and the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

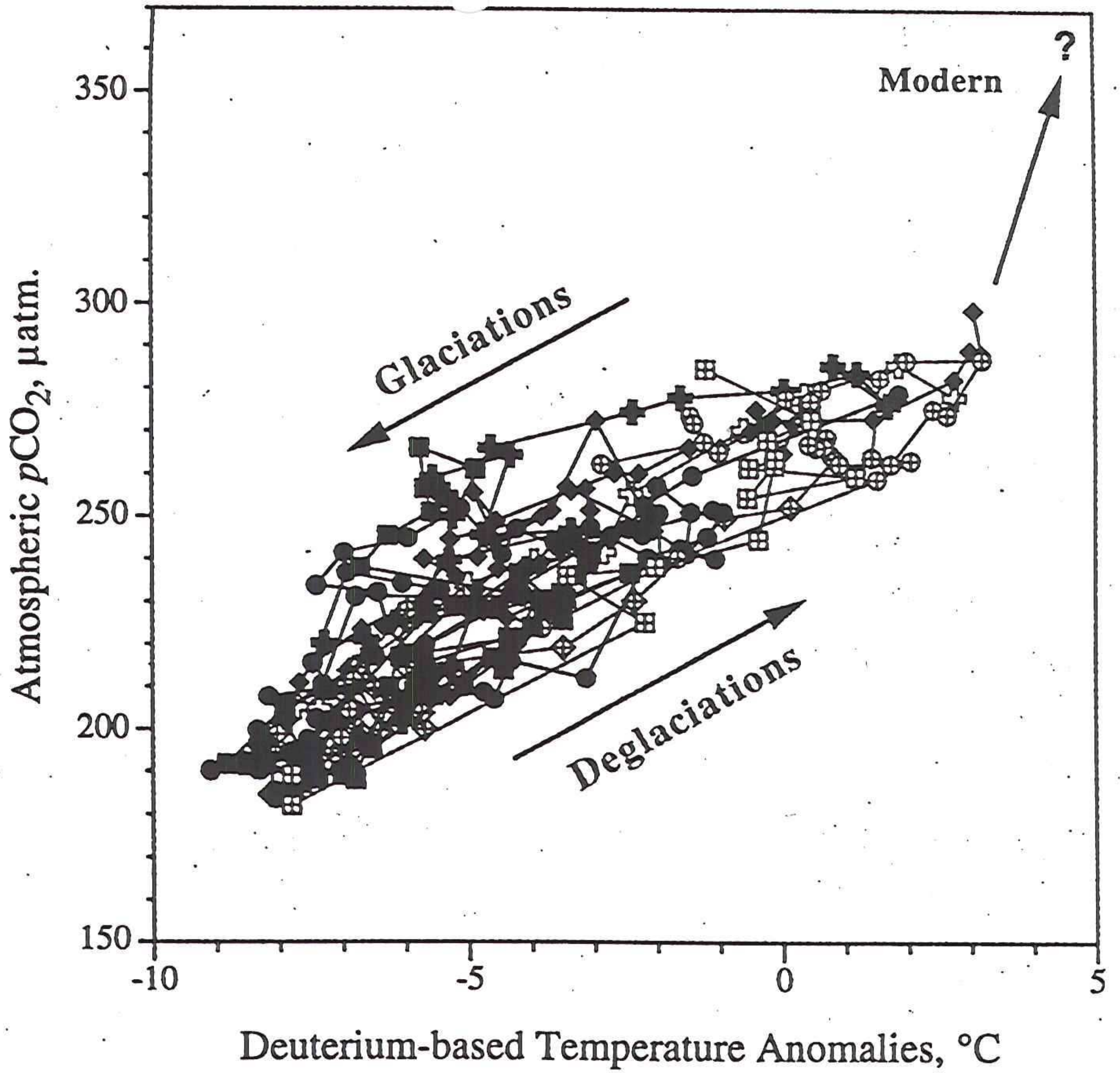
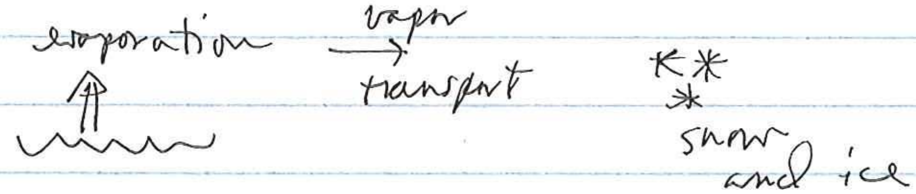


Fig. 1. A correlation between atmospheric partial pressure of CO_2 (pCO_2) and isotopic (δ_D) temperature anomalies as recorded in the Vostok ice core. The figure shows that climate variations in the past 420,000 years operated within a relatively constrained domain. Data are from (*8*).

01/06/04 — How I think this works

isotopically light water evaporates more easily than heavy ⇒ ice is isotopically lighter than the water from which it is derived



<u>Benthic</u> forams — live in deep water — temp very stable — mostly sensitive to <u>ice volume</u> — measure $^{18}O/^{16}O$ in $CaCO_3$ in foram <u>shells</u> ⇒ $^{18}O/^{16}O$ ~~[illegible]~~ is <u>high</u> during glacials — shells form in the isotopically heavy water — <u>proxy for ice volume</u>

δD or D/H in ice is mostly a temperature effect — ~~[illegible]~~ <u>proxy for air temp in Antarctica</u>

Question can be posed in 2 ways.

What will CO_2 vs time look like for a given emission scenario.

Projection of emission rate (currently 5.5 GtC/yr) is very difficult.

Depends on rate of population growth, industrialization, use of alternative technologies

A wide range of scenarios can be imagined – from drop to pre-industrial levels to increases by ~ factor of 10 in next 100 years

IPCC scenarios a–f

↑ Intergovernmental Panel on Climate Change

Models yield resulting CO_2 in atmosphere — oceanic uptake rate is main thing modelled — feedbacks are not taken into account, e.g. CO_2 fertilization

Highest model is not outlandish — assumes moderate population growth, high economic growth, and a phase out of fossil fuel — all desirable from other points of view.

It predicts 3× pre-industrial level in 2100

Note too that none are stabilized.

All are still climbing in 2100!

Three variables in these projections

- rate of population growth r_t
- rate of growth of per capita energy consumption
- % energy supplied by nuclear fuel

Suppose e.g. that r_t remains at 1.6% and that per capita energy consumption & % fossil fuel remain same — no economic growth

~ 5 × present

Population in 2100 = $(1.016)^{100}$ = 4.9 × present

$$\overset{5}{\cancel{(4.9)}}\,(5.5\ \mathrm{GtC/yr}) = 27\ \mathrm{GtC/yr}$$

$$\overset{5}{\cancel{(4.9)}}\,(7.1\ \mathrm{GtC/yr}) = 35\ \mathrm{GtC/yr}$$

~30 ~~28~~ billion people

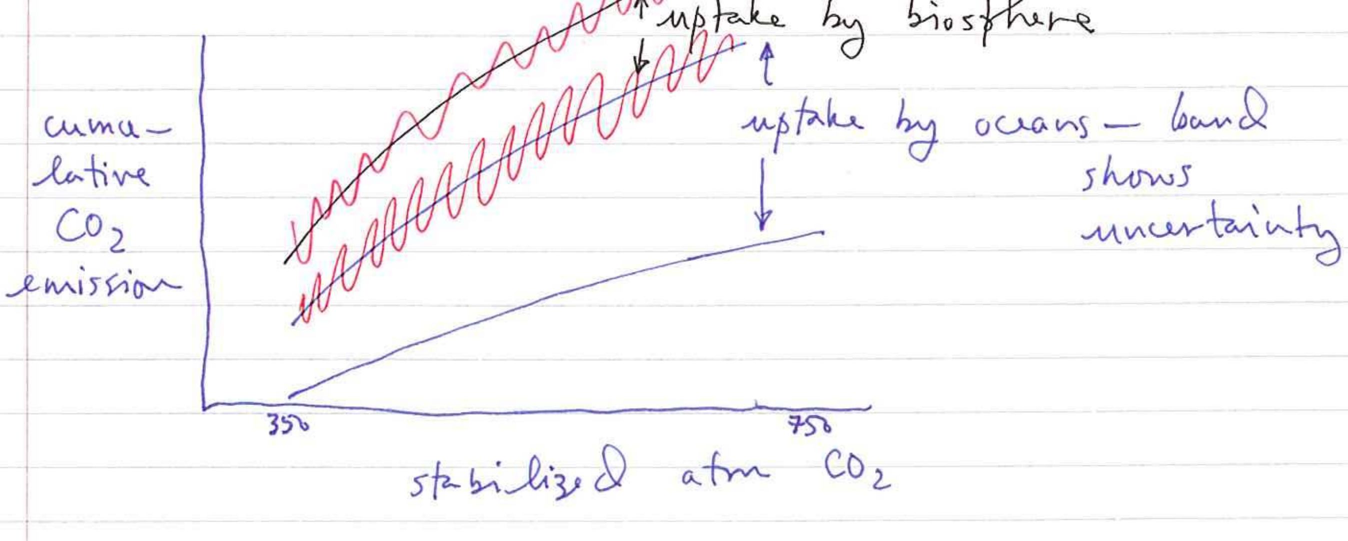
Can turn problem around & ask: What must our emission rates look like if we wish to stabilize atmospheric CO_2 at a new post-boom steady state.

Five IPCC scenarios $\overset{\text{current}}{350\ \text{ppm}} \rightarrow 750$ ppm

To stabilize at 450 ppm, we have to start decreasing emission rates immediately.

To stabilize at 750 ppm, we have to eventually cut back to pre-industrial levels but we can continue to grow for another century or so.

Figure 8 from the IPCC report shows the cumulative anthropogenic emission versus the final stabilized concentration in the atmosphere



Cumulative emission so far — since industrial revolution — 300 GtC

[illegible]

Suppose we were to burn all 2000 bbl of pumpable oil left in the "reserves"

1 bbo releases 5.8 quads and 0.12 GtC into atmosphere

At current rate 25 bbl/day this would last < 100 yrs ⇒ ≈ 2100

This would provide 12,000 quads of power and release

240 GtC — 2000 bbl oil — 12,000 quads

on third thought — do the US coal example instead — page 13 1/2

Cumulative emission would then be

$300 + 240 = 540$ GtC

650 ppm =

This ⇒ ~~750 ppm~~ in atmosphere

2.3 X × pre-industrial

= ~~2.7 × pre-industrial~~

WRONG

do it this way
2400 GtC emission
⇒ 800 GtC in atm
= 3X pre-industrial

the abscissa in Fig. 1.14 is emission since 1900 ⇒ don't add the 300

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

	GtC released / quad of energy
gas	0.015
oil	0.02
coal	0.025
shale oil	0.03 – 0.11

Dilemma : least CO_2 friendly — coal — 1.7 × as much CO_2 released per quad as gas — is by far the most abundant — particularly in US

Switch to carbon friendly gas will entail

Say the US were to burn all of its 280 Gt of coal reserves

This would yield

$(280 \text{ Gt coal})(28 \text{ quads / Gt coal})$

$= 7800$ quads of energy

The amount of CO_2 released into atmosphere would be

$(7800 \text{ quads})(\overset{0,025}{} \text{ GtC / quad})$

$= 200$ GtC released

200 GtC

$\Rightarrow$ atmospheric CO_2 = 450 ppm

$\approx$ 1.6 × pre-industrial

Dilemma — coal — least CO_2 friendly (1.7 × as much CO_2 released per quad of energy as gas) is by far most abundant in US.

Switch to CO_2 friendly gas will entail increasing reliance upon foreign sources.

increasing reliance upon foreign sources for US.

None of the above is in dispute.

All scientific experts agree.

If we release GtC previously buried in sediments 2–7 km deep it must go somewhere.

At present 3.2 of 7.1 GtC/yr or 45% go into atmosphere.

~~Models indicate that a stabilization at 7~~

Stabilization at 750 ppm = 2.1 x present ⇒ atmospheric reservoir will be (2.1)(760 GtC) = 1560 Gt

Increase = 1560 − 760 = 800 GtC

Agrees with Fig. 8

Pre-industrial atmospheric reservoir was 625 GtC rather than 760 GtC

Why — total emissions 300 GtC — 45% of this is 135 GtC — 760 minus 135 = 625 GtC pre-industrial atmospheric reservoir

Here is the way to use the figure 1.14

To stabilize atmospheric CO_2 at $2\times$ pre-industrial = 560 ppm
can emit no more than

1400 GtC more

This in addition to 300 GtC already emitted. The uncertainties account for differences in the temporal pattern of emission — not very sensitive to this — mostly to total amount released.

Burning of all US coal reserves:

280 Gt coal × 28 quads/Gt coal × 0.025 GtC/quad = 200 GtC US coal

Burning of world-wide oil reserves:

2000 bbo × 5.8 quads/bbo × 0.02 GtC/quad

= 230 GtC — world oil

World coal — 3000 Gt coal × 28 quads/Gt coal × 0.025 GtC/quad = 2100 GtC world coal

To stabilize at present value 360 ppm — can emit no more than another 300 GtC

Fig. 8 indicates that ~ [illegible] 45%
of anthropogenic release
continues to go into atmosphere

This thickens the greenhouse "glass".

If a rise of atmospheric CO_2

$$360 - 280 = 80 \text{ GtC} \rightarrow 2 \text{ W/m}^2$$
$$\Rightarrow 0.4°\text{C}$$

Then a [illegible] doubling $(2 \times CO_2)$

[illegible]

$$280 \rightarrow 2 \times 280 \Rightarrow 2\left(\frac{280}{80}\right) = 7 \text{ W/m}^2$$
forcing

⇒ 1.4° C rise
due to purely
radiative effects
$(2 \times CO_2)$

[illegible] 1.3°
better value

$$\boxed{\frac{\Delta T}{T} = \frac{1}{4} \frac{\Delta \mathcal{U}_0}{\mathcal{U}_0}}$$

$$\Delta T = 288 \text{ K} \times \frac{1}{4} \times \frac{7}{388}$$
$$= 1.3 °\text{C}$$

But this ignores feedback effects:

Many possible effects both positive & negative

Examples:

(1) T increases ⇒ increased oceanic evaporation — H_2O also absorbs IR — <u>increased</u> warming

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

These effects must all be studied together using a <u>GCM</u> or general circulation model.

World leaders in this enterprise — GFDL

Must use a <u>coupled ocean-atmosphere</u> <u>model</u>

Temperature, precipitation, evaporation, winds, ocean currents are all simultaneously modelled — biggest users of supercomputers

Figure 7-4 from Turekian shows Manabe & Stouffer results for time-averaged climate in equilibrium with 2x CO_2

- cooling in stratosphere
- surface warming by 1.5°C — 4.5°C
  best estimate 2.5°C
- polar warming greater than

temperato

- warming of mixed layer in ocean — little change in deep ocean
- precipitation will increase
- climate extremes will increase — not only will it be 2.5°C warmer in Princeton (4.5°F) there will be more extremely hot days.

The GCM results are not as certain as the purely radiative results — cloud modelling particularly problematical

Grid size is 100 km × 100 km — larger than individual clouds — some dispute the model results completely — though they are a small — generally politically motivated — minority.

Other modellers have ~~gone even~~ gone even further — model effects of higher CO_2 & higher T on biosphere.

- Example — plants grow better on average in enriched CO_2

Fig. 5.1 (Kimball — from Graves & Reavey)

$2\times CO_2 \Rightarrow$ 36% increase in yield

$\Rightarrow$ 1% per 10 ppm increase

The response, however, is highly variable and could be affected by many other things, e.g. it is probable that N hemisphere mid-latitude dryness will increase.

One consequence is fairly well understood — rise in sea level.

Observed to be increasing at present at about 1–2 mm/yr

TOPEX – POSEIDON noisy but ~ 4 mm/yr

In 2050 sea level would be 5–10 cm higher if continues to rise at current rates

Many causes:

- mining of ground water
- retreat of valley glaciers
- thermal expansion seawater column

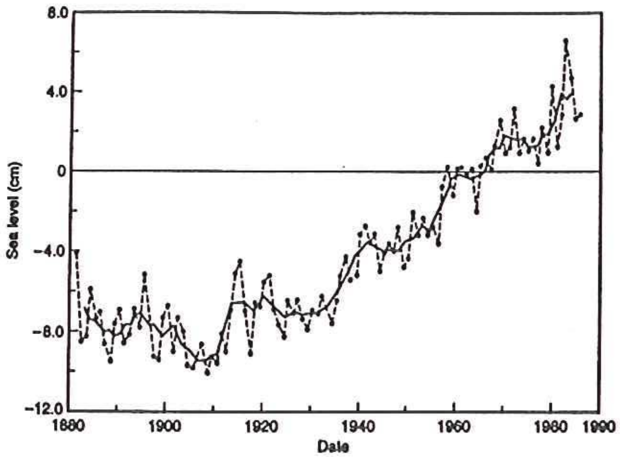
↑ main effect

Best estimates from GCMs:

5–40 cm rise by 2050

Could be serious in countries such as Bangladesh — mouth of Ganges – Brahmaputra rivers — mean elevation ~ sea level.

[2] (25%) Analysis of coastal tide gauge data shows that global mean sea level has been rising over the past century. (a) Use the graph below to find the mean rate of rise since 1900 in mm/yr.



The present rate of ground-water extraction due to overpumping of aquifers such as the Olgallala is estimated to be 2×10^{11} m³/yr. All of this water, after being used for irrigation, runs off into the oceans. (b) What fraction of the observed sea-level rise is due to this water "mining" effect? For those that don't remember---the radius of the Earth is 6371 km. The amount Δl by which a laterally constrained column of material, initially of length l, expands upon heating through a temperature interval ΔT is given by $\Delta l / l = \alpha \Delta T$. The quantity α is the coefficient of thermal expansion. For water: $\alpha_{H2O} = 3.6 \times 10^{-4}$ °C⁻¹. Suppose that the $\Delta T = 0.5$ °C surface warming over the past century has extended down to a depth $l = 300$ m in the oceans. (c) What fraction of the observed sea-level rise is due to this thermal expansion effect?

[3] This problem was not on the Prep Sheet

(a) $\frac{120 \text{ mm}}{100 \text{ yr}} \approx 1.2$ mm/yr

(b) surface area of oceans =

$0.7 \times 4\pi \times (6371 \text{ km})^2$

ocean-covered fraction

$= 3.6 \cdot 10^8 \text{ km}^2$

$= 3.6 \cdot 10^{14} \text{ m}^2$

rise due to groundwater "mining" =

$\frac{2 \cdot 10^{11} \text{ m}^3/\text{yr}}{3.6 \cdot 10^{14} \text{ m}^2}$ [illegible]

[illegible]

= 0.56 mm/yr

46% of observed

(c) $\Delta l = 3.6 \cdot 10^{-4}\ {}^{\circ}C^{-1}$

$\times\ 0.5\ {}^{\circ}C \times 3 \cdot 10^{5}$ mm

$= 54$ mm in 100 years

≈ 0.54 mm/yr

45% of observed

Do not count off if they round more than this, since none of these estimates are more precise than ~ 1 figure.

Any "leftover" sea-level rise is due to melting of mountain glaciers — but the above two effects account for most of it — about half each

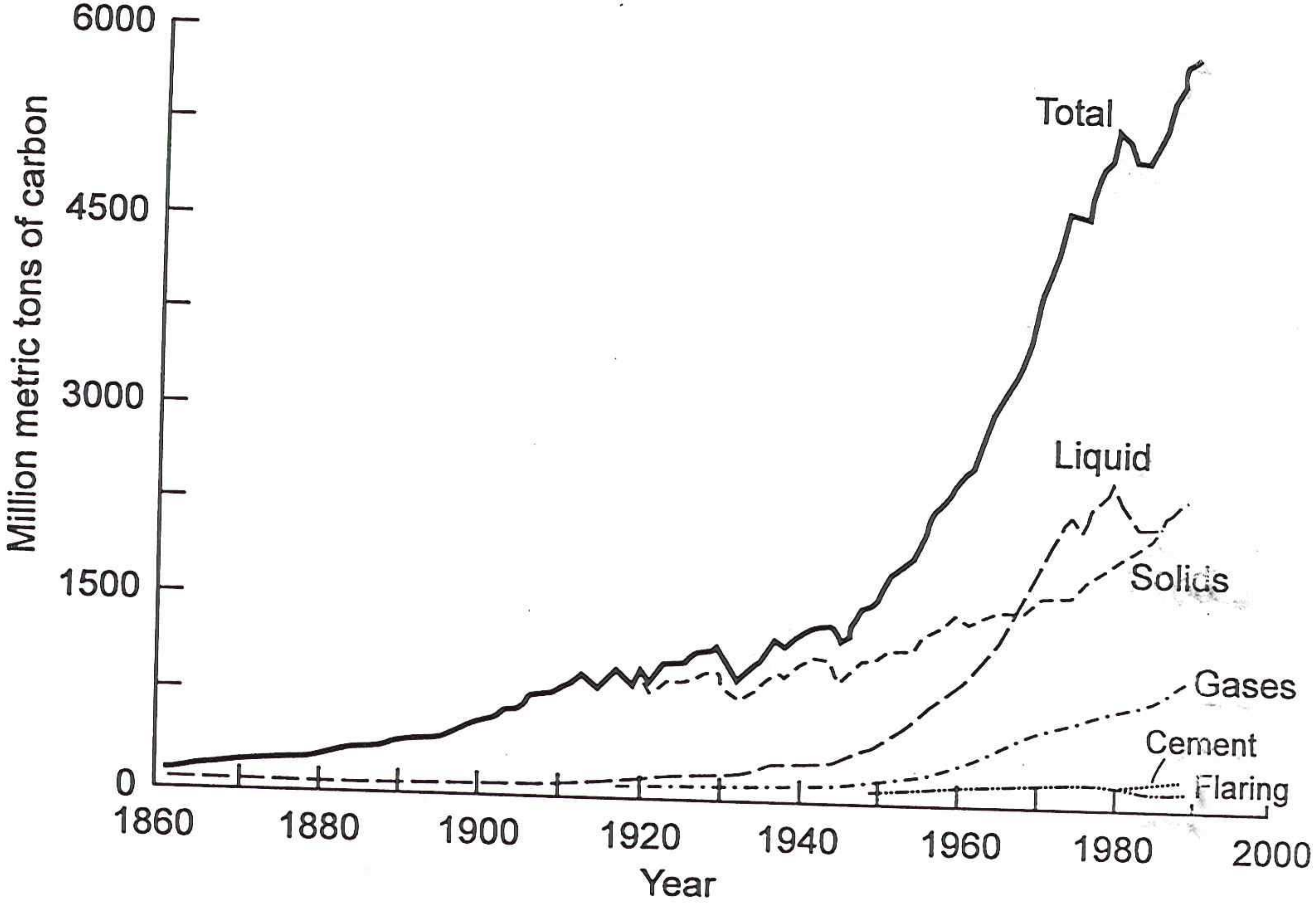
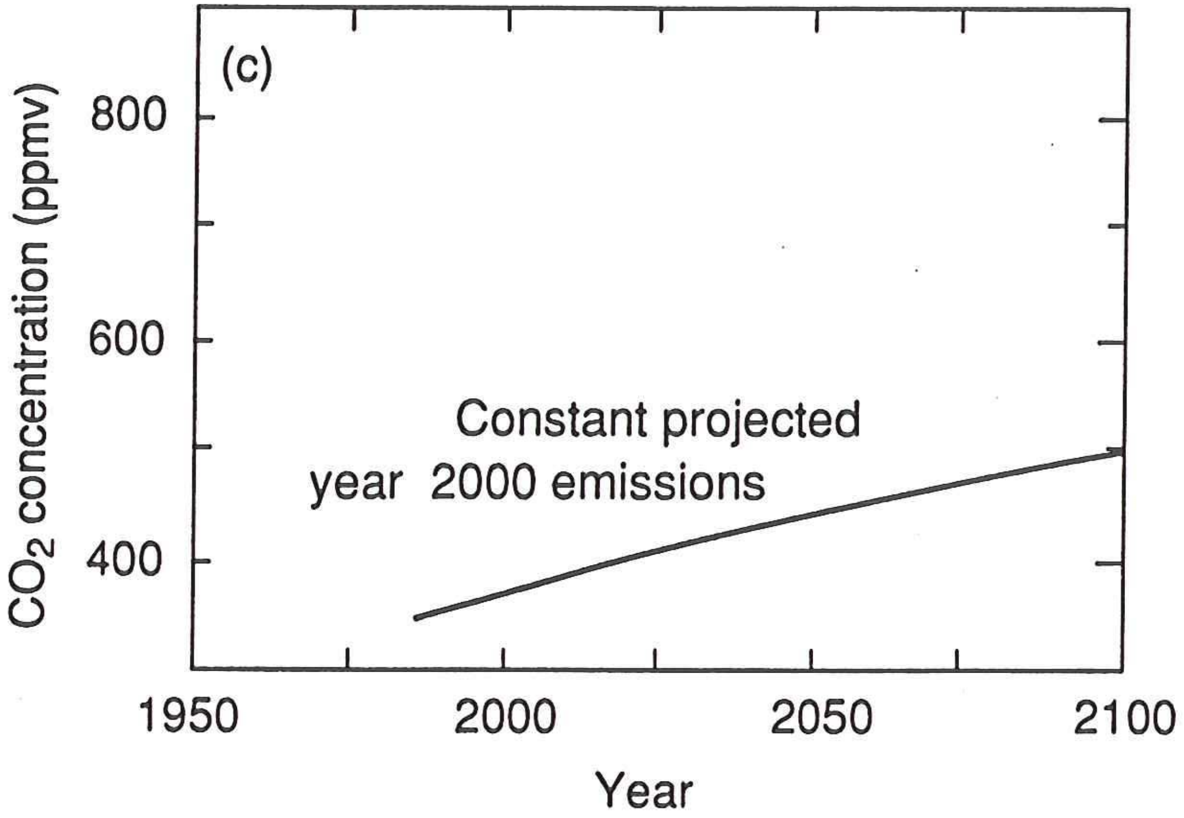


Figure 11.18. Global CO_2 emissions from fossil fuel burning and cement manufacture, 1860–1989. (From *Trends '91: A Compendium of Data on Global Change*)



(c) CO_2 concentrations resulting from constant projected year 2000 emissions (using the model of Wigley).

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

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)

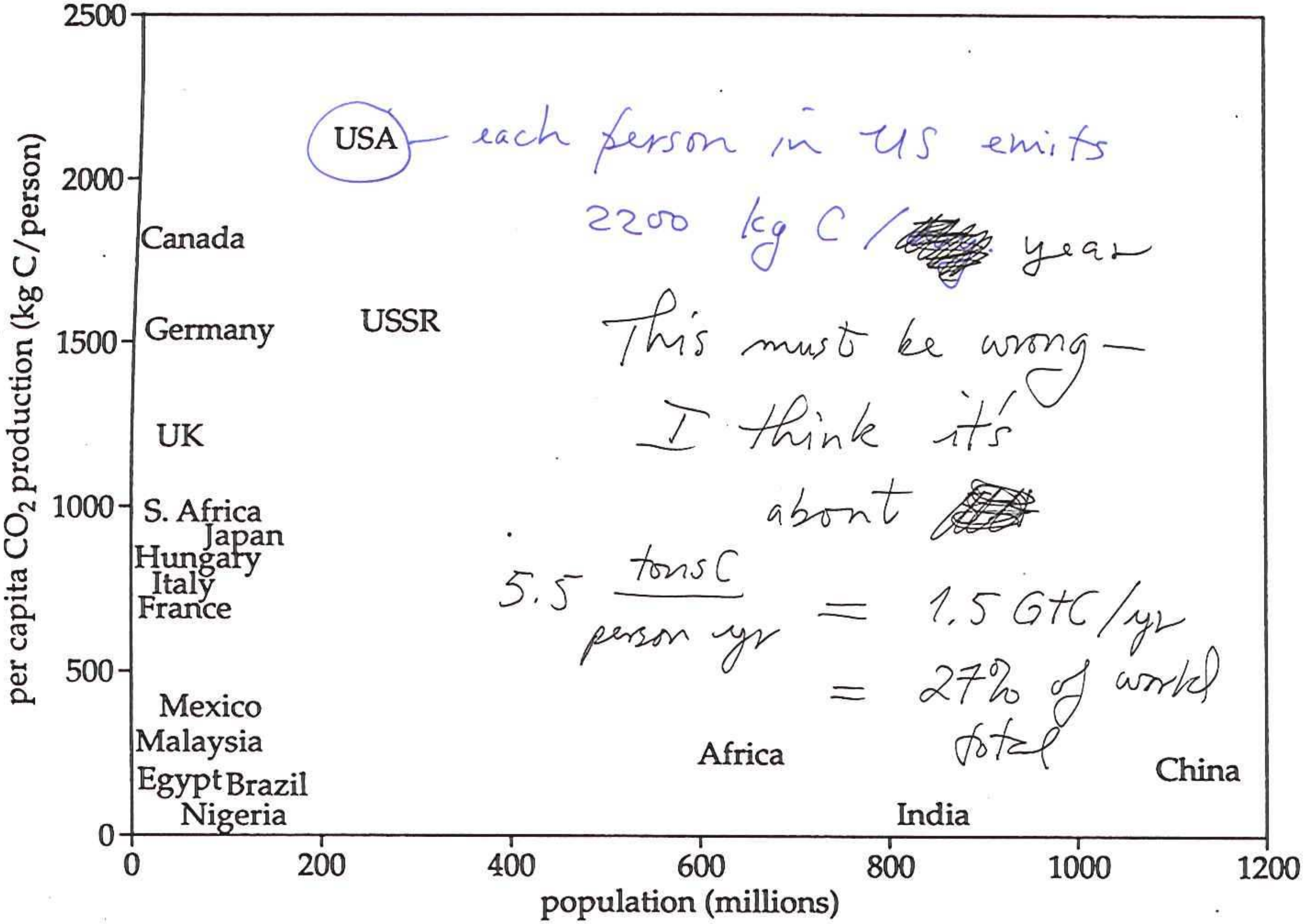


Figure 1.4 Per capita CO_2 production from fossil fuels and cement production by country or region versus population. The industrialized countries have a high per capita output of CO_2, whereas many populous developing countries produce much less CO_2 per capita. (Data from WRI 1990.)

each person in US emits 2200 kg C / year

This must be wrong — I think it's about

$$5.5 \frac{\text{tons C}}{\text{person yr}} = 1.5 \text{ GtC/yr} = 27\% \text{ of world total}$$

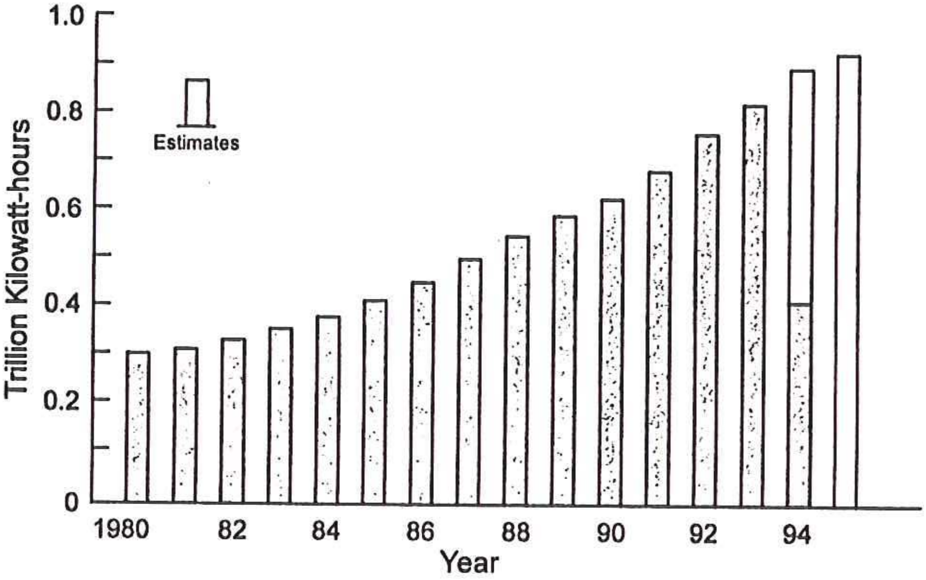
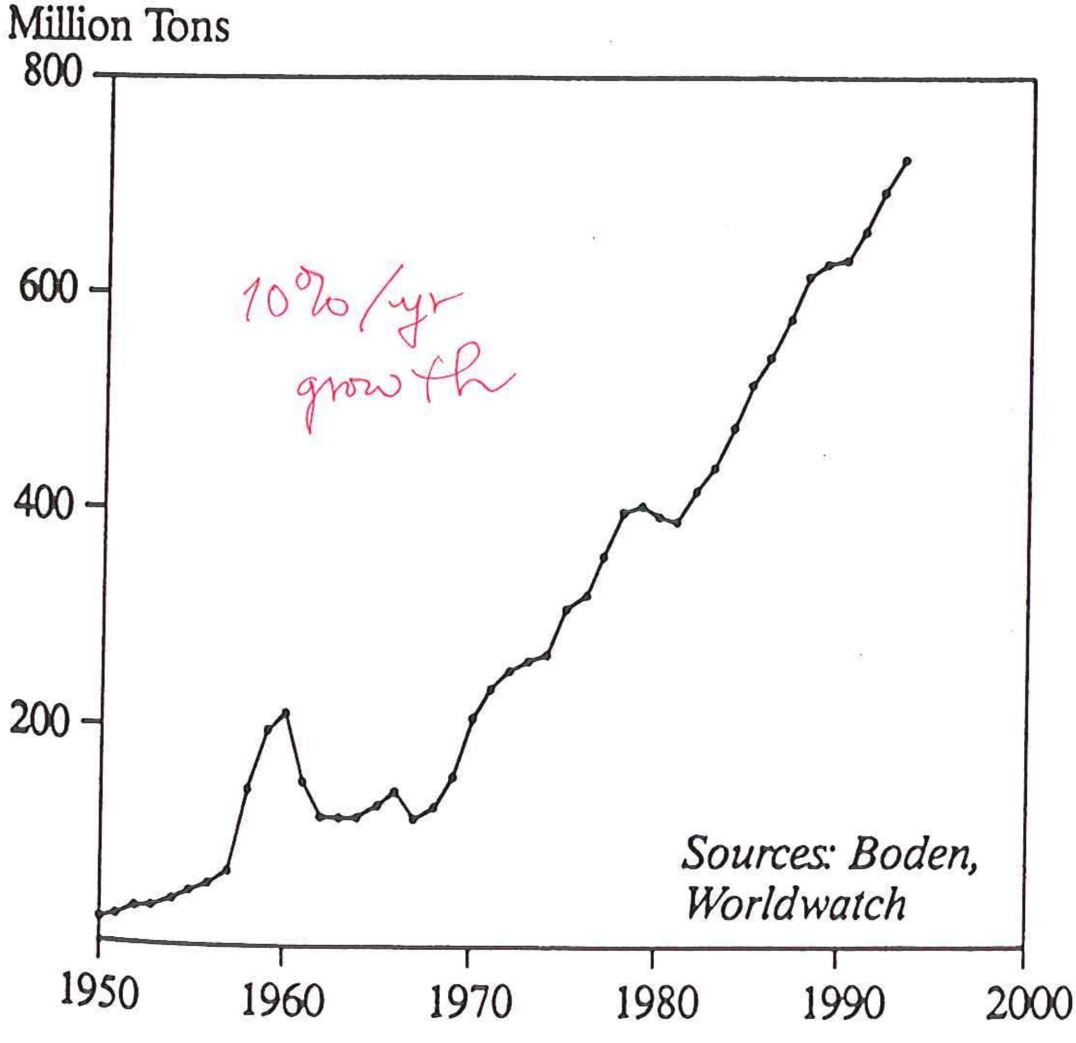


Figure 8.33b. Electricity generation in China since 1980. (*New York Times*, November 7, 1994)



10%/yr
growth

Sources: Boden, Worldwatch

Figure 7-4. Carbon Emissions in China, 1950–93

7.1 GtC/yr →
now

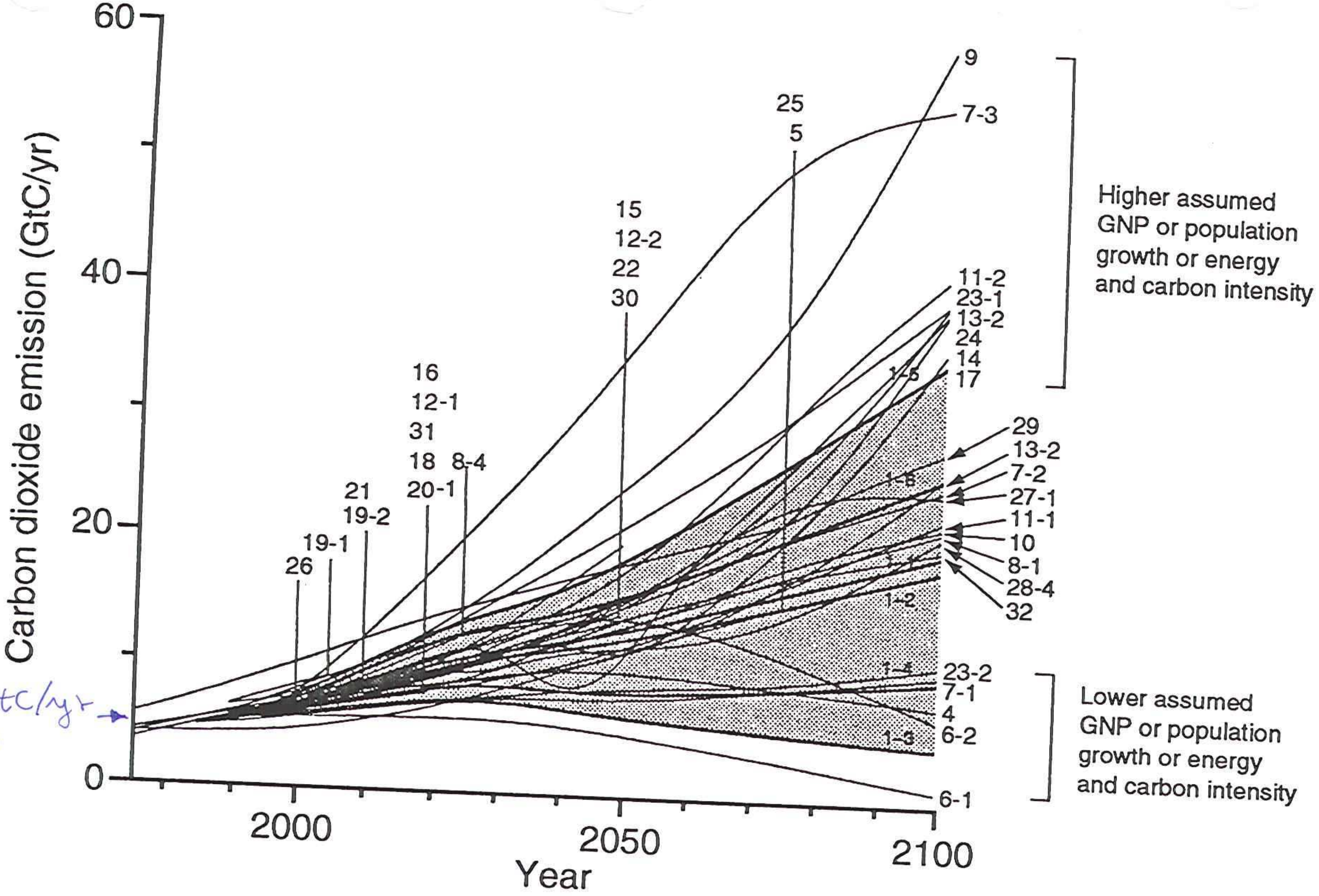
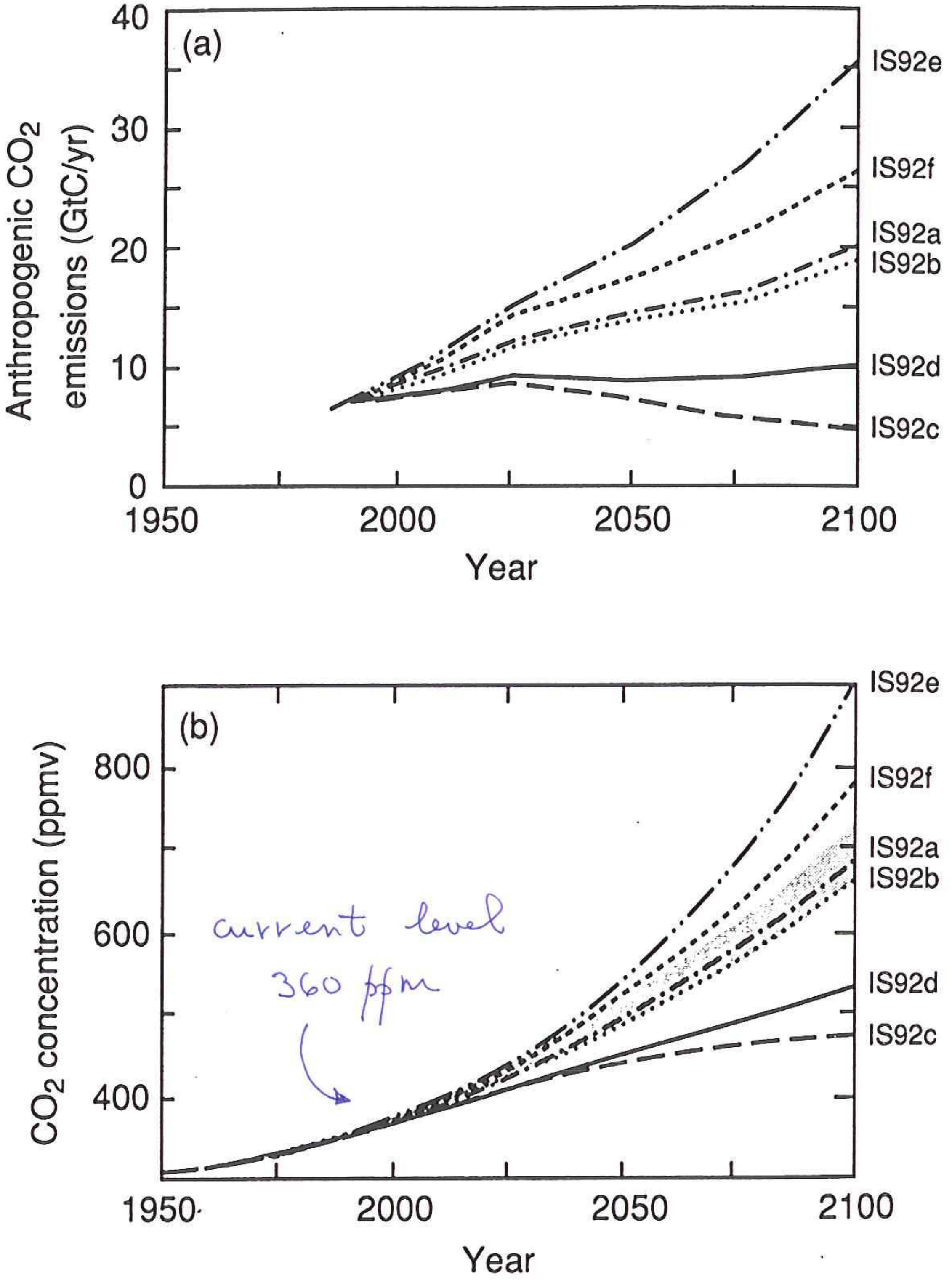


Figure 6.1: Energy-related global CO_2 emissions for various scenarios. Shaded area indicates coverage of IS92 Scenarios. Numbers correspond to list of scenarios in the Supplementary Table.



current level
360 ppm

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)

IPCC Intergovernmental Panel on Climate Change

"Dial – a – Climate"

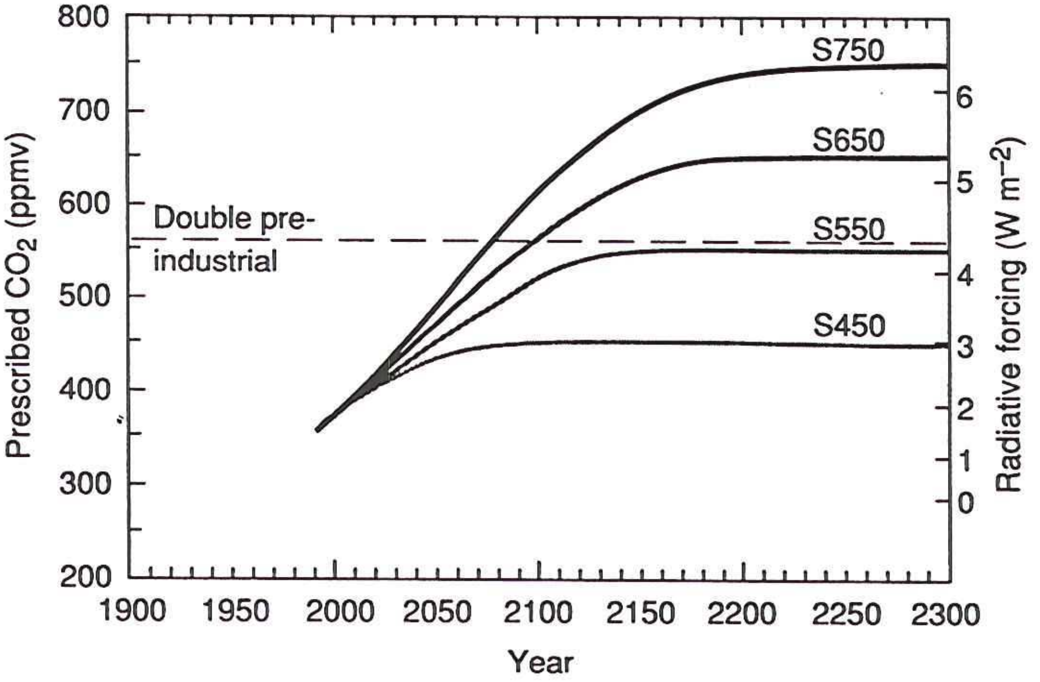
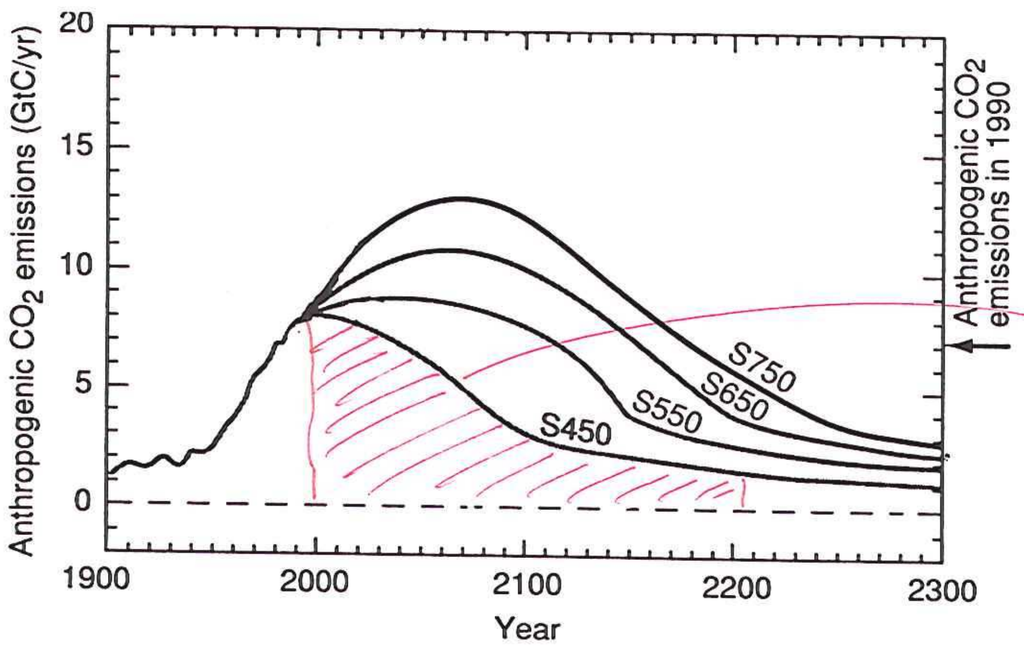


Figure 6: Profiles of atmospheric CO_2 concentration leading to stabilisation at 350, 450, 550, 650 and 750 ppmv. Doubled pre-industrial CO_2 concentration is 560 ppmv. The radiative forcing resulting from the increase in CO_2 relative to pre-industrial levels is marked on the right-hand axis. Note the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



red shows cumulative emissions through 2200 to stabilize at 450 ppm

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.

approximately 200 yrs
× 4 GtC/yr ≈
800 GtC cumulative
(see next page)

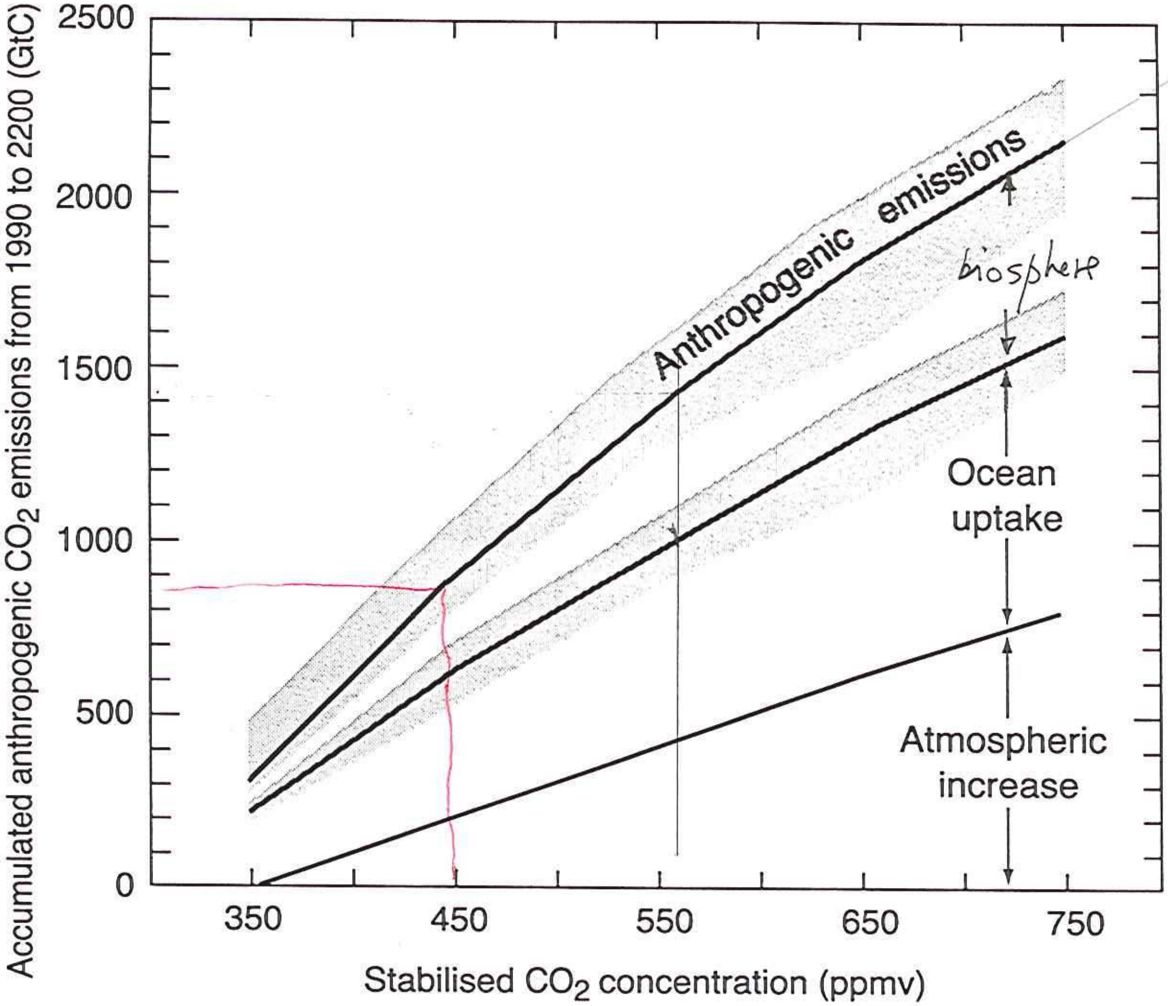


Figure 1.14: Accumulated anthropogenic CO_2 emissions over the period 1990 to 2200 (GtC) plotted against the final stabilised concentration level. Also shown are the accumulated ocean uptake and the increase of CO_2 in the atmosphere. The curves for accumulated anthropogenic emissions and ocean uptake 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.

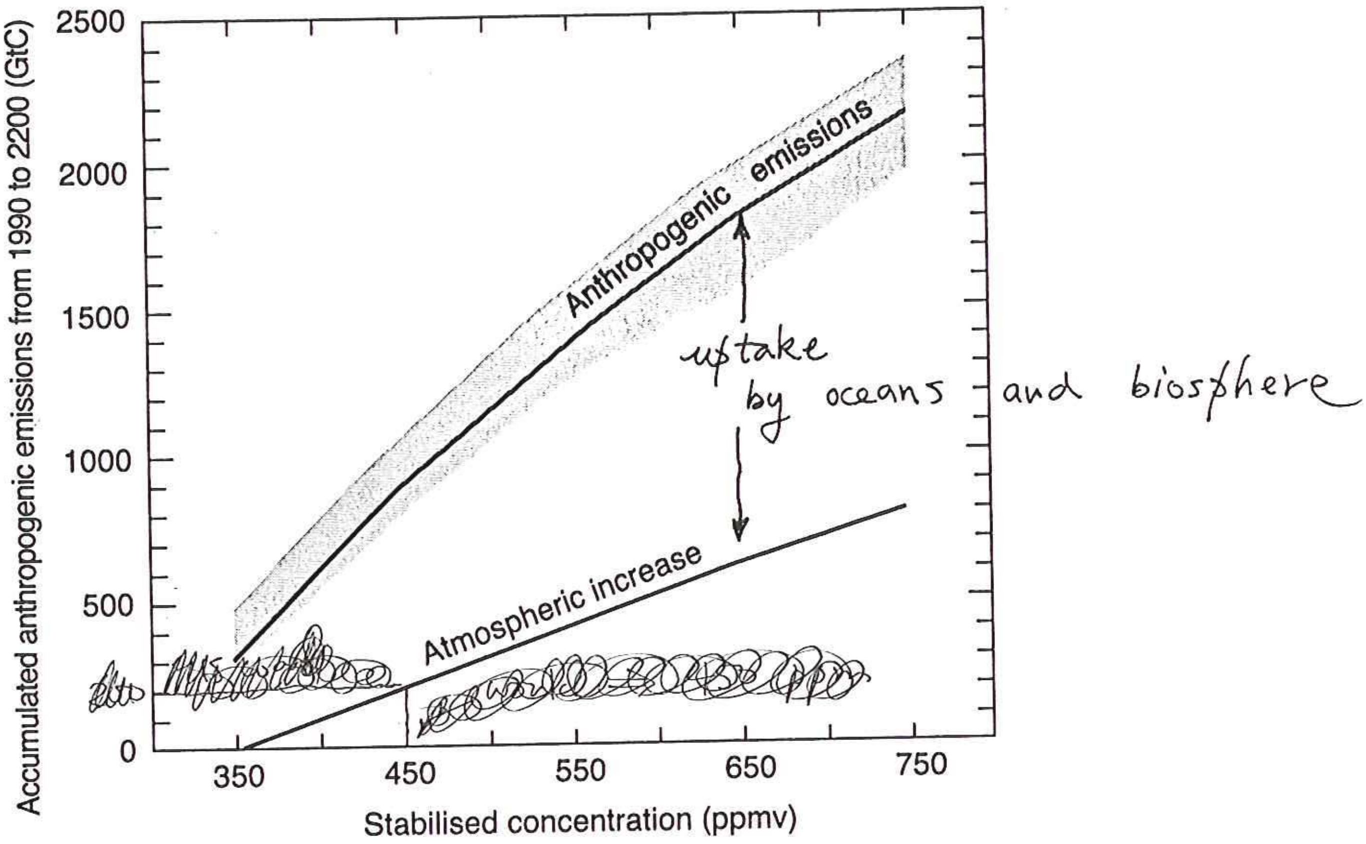


Table 11. Carbon dioxide emission rates for different fuels [in kg °C (in CO_2) per million BTU energy].

Fuel	kg C per MBTU[a]	Adopted[b]	GtC / quad
Natural gas	14–15	14.5	0.014
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.

Table 4.1
CO_2 Emission Factors for Fuel Data Before 1950

Fuel	Carbon Content	Oxidized to CO_2 (percent)	CO_2 Factor (tons C/ton fuel)	$\frac{\text{GtC released}}{\text{quad of energy}}$
Coal	70%	99	0.693	
Lignite	28%	99	0.277	
(Coal plus Lignite as coal equivalent)	(69%)	(99)	(0.683)	0.025
Crude Petroleum	84%	91.5	0.769	0.020
Natural Gas	540 g/m^3	97	0.524×10^{-3}[a]	0.015

[a] Tons of carbon per m^3.

Source: Keeling (1973).

Table 4.2
Factors and Units for Calculating Annual CO_2 Emissions from Global Fuel Production Data

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$$CO_{2_i} = (P_i)(FO_i)(C_i)$$

From Natural Gas Production

CO_{2_g} = CO_2 emissions in 10^6 t C
P_g = Annual production in thousands of 10^{12} joules (±~10%)
FO_g = Effective fraction oxidized in year of production = 0.98 ± 1%
C_g = Carbon content in 10^6 t per thousands of 10^{12} joules = 0.0137 ± 2%

From Crude Oil and Natural Gas Liquids Production

CO_{2_l} = CO_2 emissions in 10^6 t C
P_l = Annual production in 10^6 t (±~8%)
FO_l = Effective fraction oxidized in year of production = 0.918 ± 3%
C_l = Carbon content in tons C per ton crude oil = 0.85 ± 1%

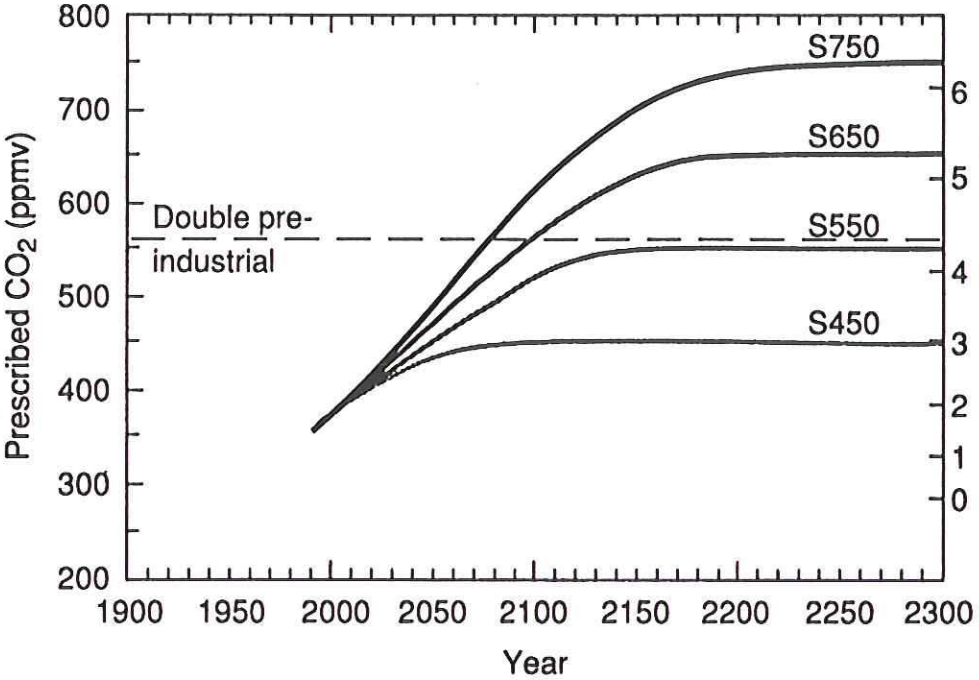
From Solid Fuel Production

CO_{2_s} = CO_2 emissions in 10^6 t C
P_s = Annual production in 10^6 tce (± ~11.2%)
FO_s = Effective fraction oxidized in year of production = 0.982 ± 2%
C_s = Carbon content in tons C per tce. = 0.746^a ± 2%

From Natural Gas Flaring

CO_{2_f} = CO_2 emissions in 10^6 t C
P_f = Annual gas flaring in 10^9 m^3 (± ~20%)
FO_f = Effective fraction oxidized in year of flaring = 1.00 ± 1%
C_f = Carbon content in tons per 10^3 m^3 = 0.525 ± 3%

Note: Units are consistent with fuel production data compiled in U.N. Energy Statistical Yearbook in 1983. All masses are in metric tons (10^6 g).



increased forcing in W/m^2

Increase to 2x pre-industrial will increase the radiative forcing by an amount

$$\delta \mathcal{U}_0 = 4.5 \quad W/m^2$$

The resulting radiative temperature increase (feedback effects ignored) will be

$$\frac{\Delta T}{T} = \frac{1}{4}\,\frac{\delta \mathcal{U}_0}{\mathcal{U}_0} = \frac{1}{4}\left(\frac{4.5}{388}\right)$$

$$\boxed{\Delta T = 0.9\ C}$$

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.

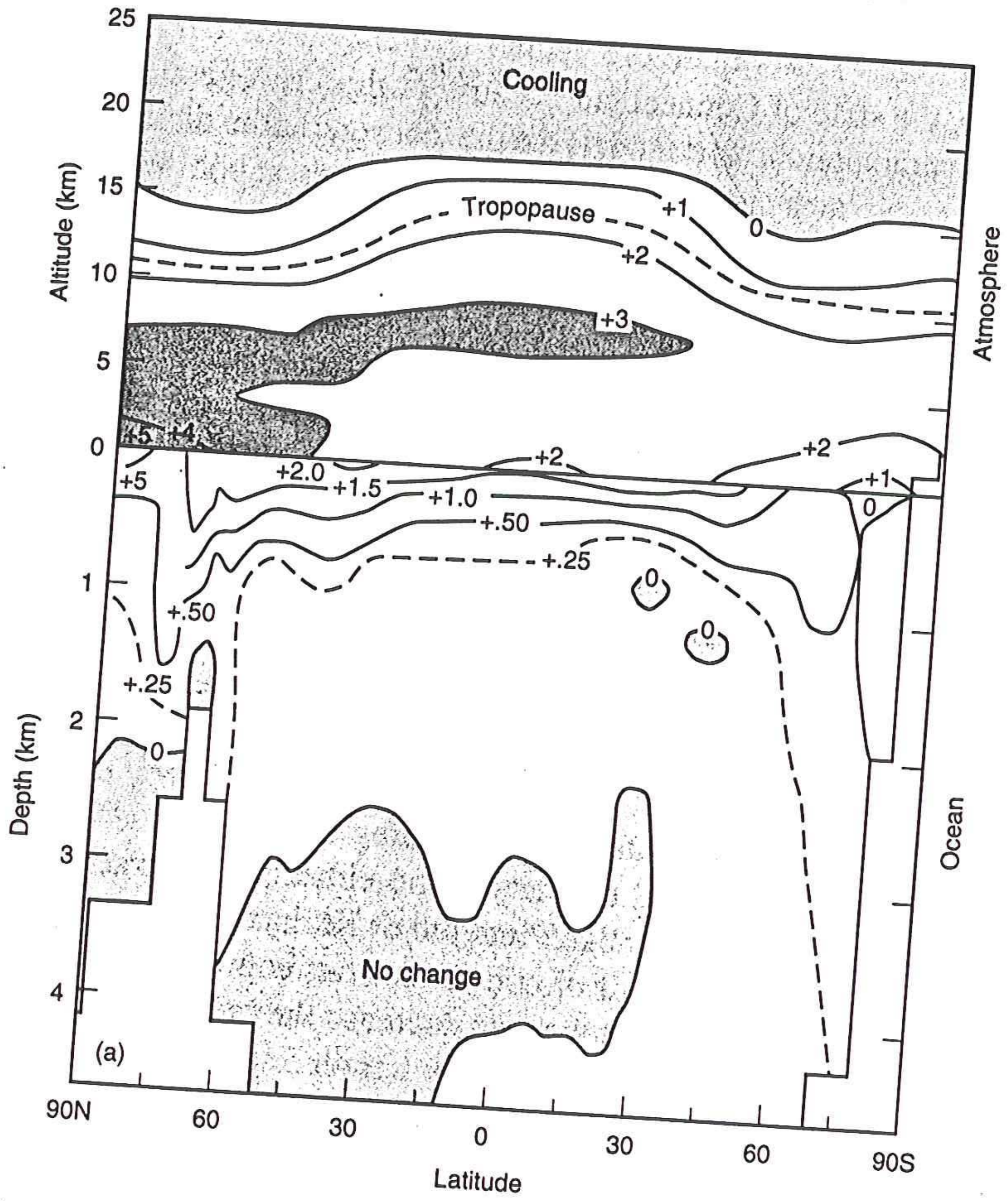
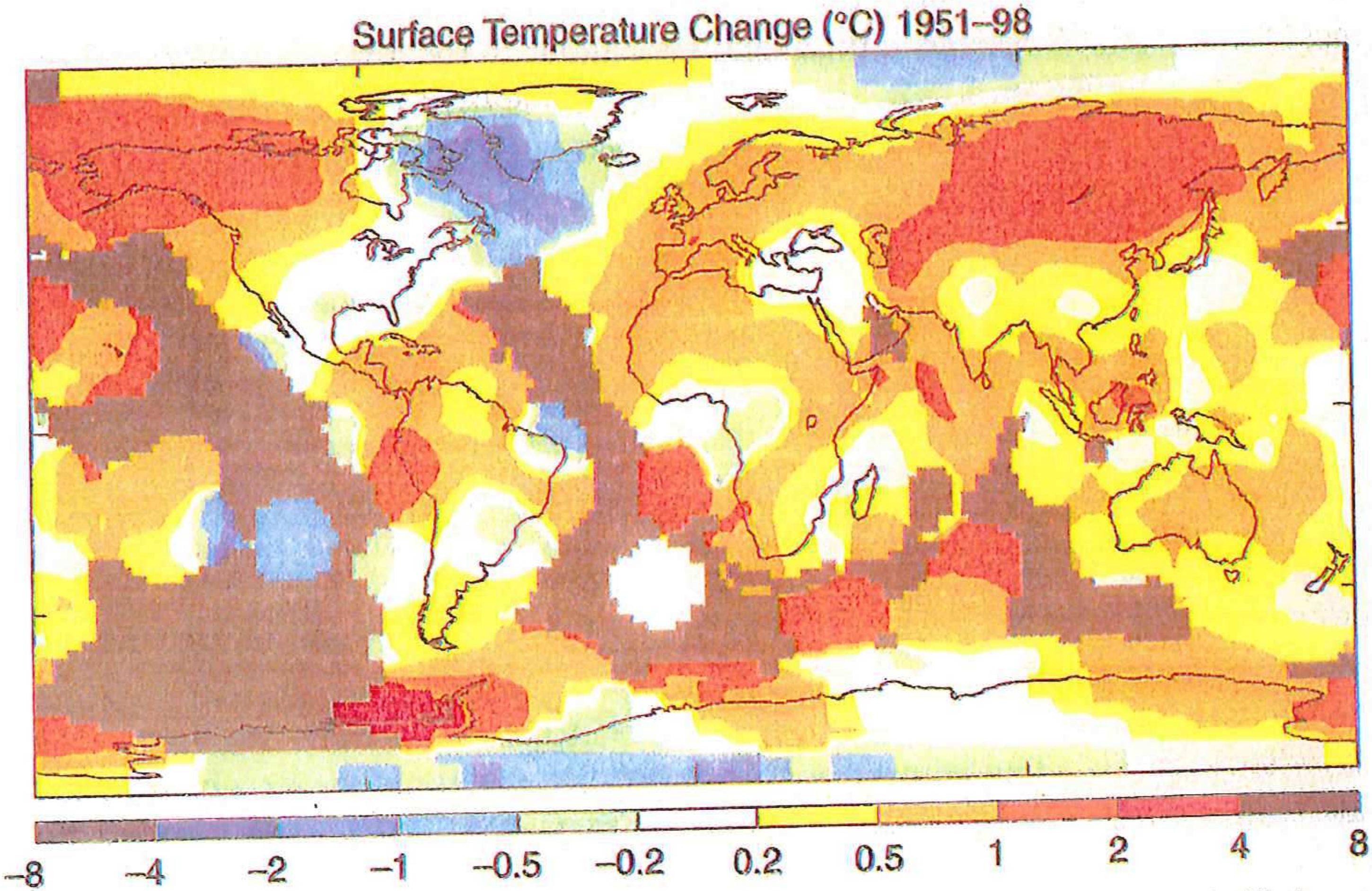


FIGURE 7–4 The changes in atmospheric and oceanic temperatures (in degrees Celsius) predicted by a general circulation model (GCM) for a doubling of the CO_2 concentration in the atmosphere from the present value based on a coupled ocean-atmosphere model. The projected doubling of CO_2 will occur in 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.)



Surface Temperature Change (°C) 1951–98

No return. Even if the goals of the Kyoto Protocol are reached, the recent half-degree warming widely attributed to rising levels of greenhouse gases won't go away for millennia.

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.

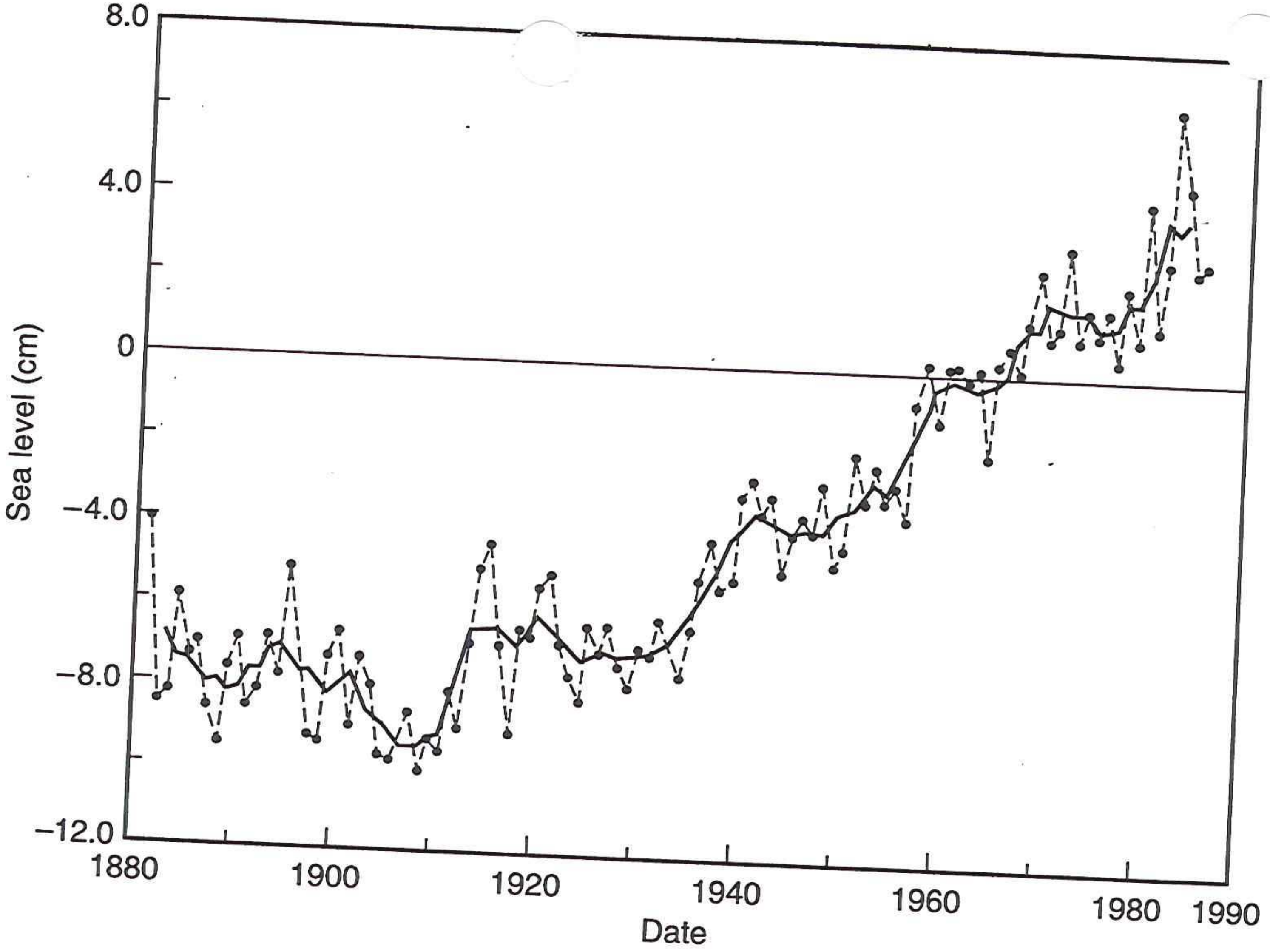


FIGURE 6–2 Global mean sea-level rise over the last century. The baseline is obtained by setting the average for the period 1951–1970 to zero. The dashed line represents the annual mean, and the solid line the 5-year running mean. (From T. P. Barnett, 1988, National Climate Program, NOAA. Reproduced in *Climate Change*, 1990, Report of IPCC Working Group 1, Cambridge University Press.)

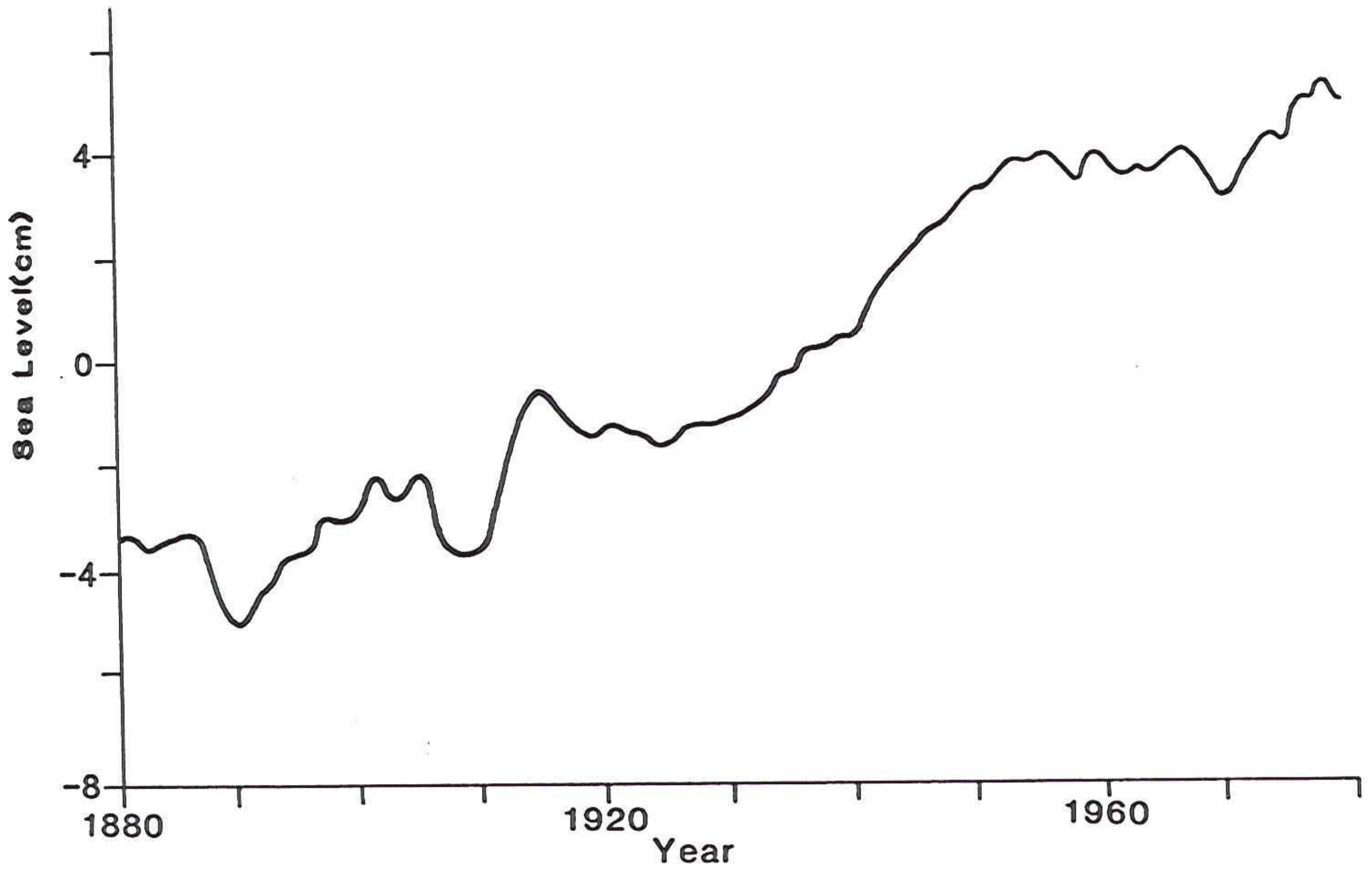


Figure 24.13. Sea-level rise, 1880–1980 (5-y averages). (Gornitz, Lebedeff, and Hansen, 1982.)

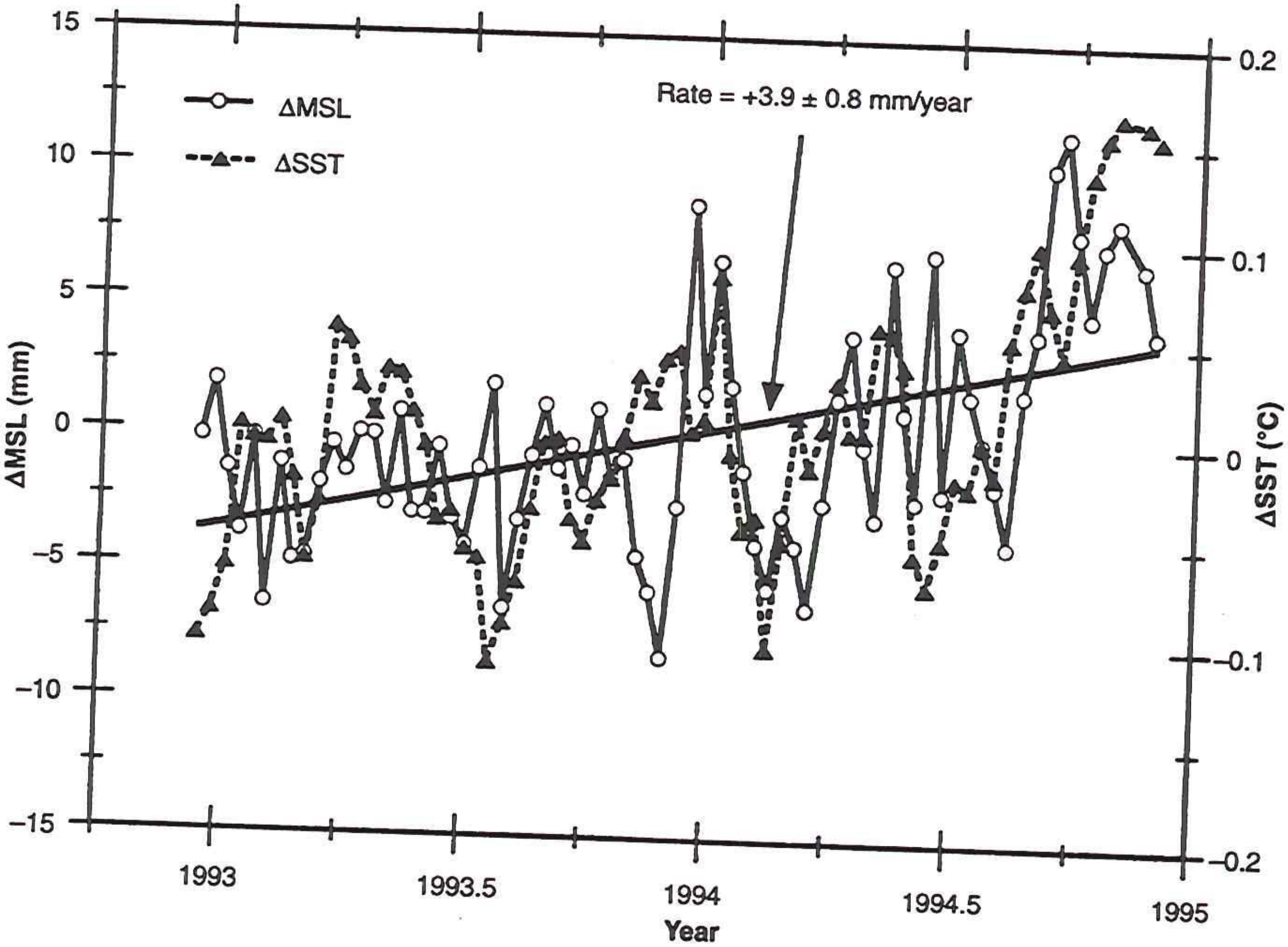


FIGURE 6–10 Global sea-level rise (ΔMSL = change in mean sea level) between 1993 and 1995 as measured by the TOPEX/POSEIDON satellite compared with global sea surface temperature rise (ΔSST = change in sea surface temperature) for the same period. (Reprinted with permission from R. S. Nerem, 1995, *Science,* v. 268, p. 708. Copyright American Association for the Advancement of Science.)

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.*

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

The New York Times

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

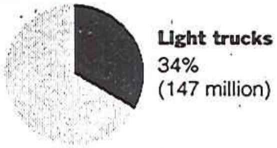
Source: *International Energy Agency*

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.

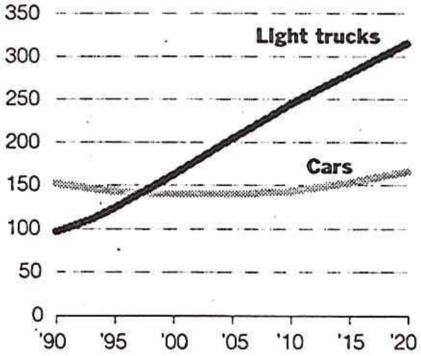
Light trucks are expected to account for 34 percent of the increase in total energy-related carbon emissions from 1990 to 2010. That total will be 32 percent higher than the 1990 level.

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

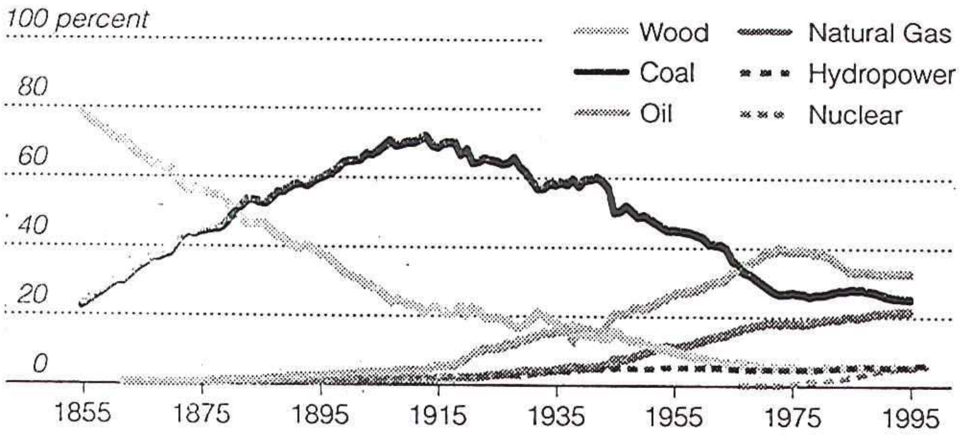
NEW YORK TIMES **NATIONAL** *SUNDAY, OCTOBER 31, 1999*

INDICATORS

Less Reliance on Carbon, but Continuing Worries About the Climate

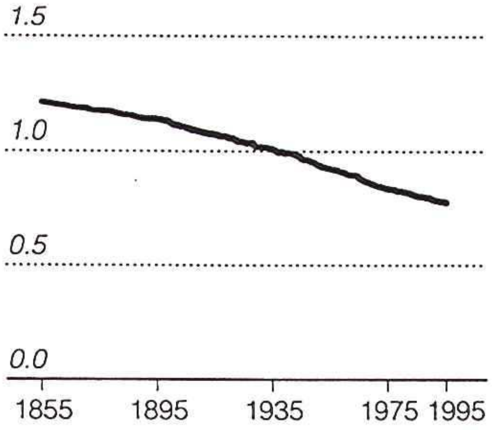
Changes in industry and technology have brought a shift in energy sources from high-carbon fuel like wood and coal to lower carbon fuels like oil and natural gas.

SHARE OF GLOBAL ENERGY CONSUMPTION



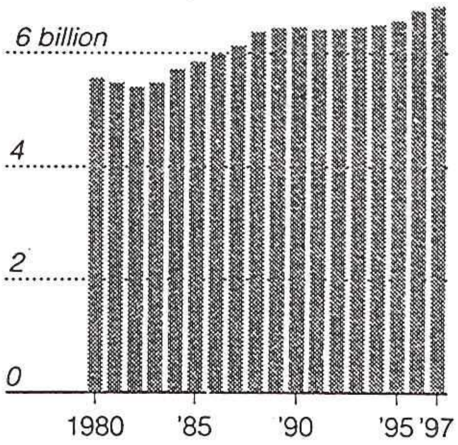
This change has meant a decline in the amount of carbon emitted in the production of a unit of energy.

CARBON EMITTED PER UNIT OF OIL-EQUIVALENT ENERGY (IN TONS)



But the total amount of carbon released into the atmosphere has continued to rise.

GLOBAL CARBON DIOXIDE EMISSIONS (IN TONS)



Source: International Institute for Applied Systems Analysis

The New York Times

THE NEW YORK TIMES **INTERNATIONAL** SUNDAY, DECEMBER 8, 1996

U.S. Taking Cautious Approach in Talks on Global Warming

By JOHN H. CUSHMAN Jr.

WASHINGTON, Dec. 7 — The Clinton Administration is taking a cautious approach toward negotiations this coming week on new measures to head off global warming due to air pollution.

In a statement to be delivered to other delegates at a United Nations meeting starting Monday in Geneva, American officials will argue that it would be unrealistic to set new deadlines for reducing emissions of so-called greenhouse gases before the year 2010. And it is too early in the negotiations to specify how big any such reductions should be, they said.

The United States, like other industrial countries, is already experiencing difficulties reducing its own emissions of carbon dioxide from burning fossil fuels. It will be very complicated persuading 153 nations to agree on how strict any new controls should be and on how they should be put into force.

The countries that signed the original climate-change treaty at the Earth Summit in Rio de Janiero in 1992 have since concluded that it ought to be strengthened. The original treaty called for industrial nations, as a first step, to aim at reducing their greenhouse gas emissions by the year 2000 to the levels of 1990. But that goal was not binding, and few nations have met it.

So the treaty partners are now trying to agree on expanded measures to control the growth of greenhouse gas emissions well beyond the turn of the century. The talks are aimed at reaching agreement at a meeting late next year in Japan.

The Administration has been arguing that the new agreement should impose binding, medium-term targets for reducing emissions to levels that are realistic and achievable, while requiring developing countries, not just industrial nations, to control their greenhouse gases.

At a briefing for reporters, a State Department negotiator said that in the Geneva meetings the United States would oppose suggestions by some countries that the next set of targets take effect as early as 2005. She added that the United States also opposes requiring all nations to adopt common policies, like uniform taxes on energy, and instead wants to provide flexibility to each nation.

The United States is urging the United Nation negotiating committee in Geneva to develop a plan that would allow some countries to pay others to make reductions on their behalf, since controlling pollution is cheaper in some places than in others and since from the planet's point of view it makes no difference where carbon dioxide comes from.

Environmentalists said they are disappointed with the Administration's approach.

"The proposal would delay the beginning of any legal requirements to reduce greenhouse pollution until at least 2010, and even then emissions could be 'borrowed' from the period after 2020," the Natural Resources Defense Council said in a statement.

"Rather than detailing commitments to protect our children, the staff paper proposes literally borrowing pollution allowances from our children and thereby putting the burden on them," said Dan Lashof of the environmental group.

But an industry coalition opposed to a binding treaty said it was pleased that the Administration "highlighted the growing attention to the economic costs" of measures to fight global warming.

"It is encouraging that the Administration apparently shares our concerns regarding impacts on the U.S. economy from poorly developed or premature policies to reduce greenhouse gas emissions," John Shlaes, executive director of the Global Climate Coalition, said in a statement.

THE NEW YORK TIMES **NATIONAL** SUNDAY, NOVEMBER 16, 1997

Agency Says Gas Emissions Will Be Worse Than Thought

By MATTHEW L. WALD

WASHINGTON, Nov. 15 — The emissions of carbon dioxide and other heat-trapping gases from energy use will grow faster than previously expected in the United States in the next few years, the Energy Department said this week. This would make it more difficult for the United States to live up to President Clinton's proposal to cap emissions of these gases at 1990 levels over the next 10 to 15 years.

The department said national economic growth would be slightly higher than previously estimated, competition would make electricity cheaper and fuel prices would not change much. More oil will be used because there will be more cars with more horsepower, and more people traveling by plane.

These factors are likely to increase emissions of greenhouse gases, produced largely through the use of fossil fuels like oil and coal, the annual energy outlook by the Energy Information Administration said.

Representatives of about 150 nations will meet in Kyoto, Japan, next month to negotiate cuts in emissions of carbon dioxide and other gases that trap heat in the atmosphere, threatening to alter the climate.

Jay E. Hakes, head of the Energy Information Administation, said that carbon emissions in 1990 were 1,336 million metric tons and that analysts had assumed that if no action were taken, the number would climb to 1,722 million by 2010. "The rough idea has been that we need to reduce carbon emissions by 28 or 30 percent to get back to 1990 levels." With the new estimate, though, the 2010 figure is 1,803 tons, which would require a reduction of close to 35 percent.

The new estimate is based on annual economic growth of 2.1 percent, up from 1.9 percent, Mr. Hakes said. Stronger growth means more disposable income and more demand for energy. The estimate is based on oil prices rising less than 10 percent by 2020, and coal prices declining 1.4 percent a year through 2020, faster than was expected last year. According to the new projection, electricity prices will drop 1 percent a year as a result of competition.

If the price of energy decreases, Mr. Hakes said, consumers and businesses will have less incentive to invest in improved energy efficiency. Lower electricity prices will also make it harder for renewable energy sources, like solar and wind power, to gain a foothold in the marketplace.

Mr. Hakes said that there were technologies with the potential to reduce carbon output, but that no new inventions or improvements of existing devices appeared likely to be in wide enough use by 2010 to upset the forecast much. Beyond that, he said, the prediction is less certain.

In fact, the department's track record for long predictions is poor. In the early 1980's, the Energy Information Administration predicted that crude oil prices could be nearly $300 per barrel by the turn of the century. The price of crude oil these days is around $20 a barrel.

U.S. Says Its Greenhouse Gas Emissions Are at Highest Rate in Years

By JOHN H. CUSHMAN Jr.

WASHINGTON, Oct. 20 — As negotiations resume in Bonn on a new treaty to save the planet from global warming, the United States said today that its emissions of heat-trapping gases into the atmosphere grew last year at the highest rate since the nation pledged to cut them back.

Emissions of carbon dioxide and other heat-trapping gases grew 3.4 percent in 1996, the latest year for which comprehensive estimates are available, the Energy Department said in a report. The department attributed the increase to strong economic growth, unusually severe weather and increased use of coal by electric utilities.

Emissions from energy use in residential and commercial buildings grew 6.3 percent and 5.5 percent, respectively, despite programs intended to increase energy efficiency.

At the same time, the report said, growing consumption of fuel by less efficient cars and light trucks suggests that motor vehicles may soon overtake industry as the largest source of gases suspected of causing global warming by effectively creating a greenhouse around Earth.

"The economy is booming, energy prices are relatively low, and a lot of people are paying a lot less attention to energy efficiency," said Steven Nadel, deputy director of the American Council for an Energy-Efficient Economy, a nonprofit research organization.

"If you have unfettered energy use and big economic growth," Mr. Nadel said, "it is not surprising that carbon emissions are going to increase. We need more active and aggressive policies. Laissez-faire does not work."

The report is acutely embarrassing to American negotiators at the climate talks, because the United State, with less than a 20th of the world's population, gives off almost a fourth of the gases that trap heat in the atmosphere, threatening widespread climate change.

In a treaty on climate change signed by 160 nations in 1992, the United States and other industrial countries pledged to reduce their emissions of such gases to 1990's level by 2000.

But American emissions in 1996 were 7.4 percent above 1990 levels, the report said. For some time the Clinton Administration has forecast that by the end of the decade, emissions of the gases in the United States will be 13 percent higher than in 1990. With the economy still growing and people driving farther in cars that use more gasoline per mile, the upward trend is widely expected to continue.

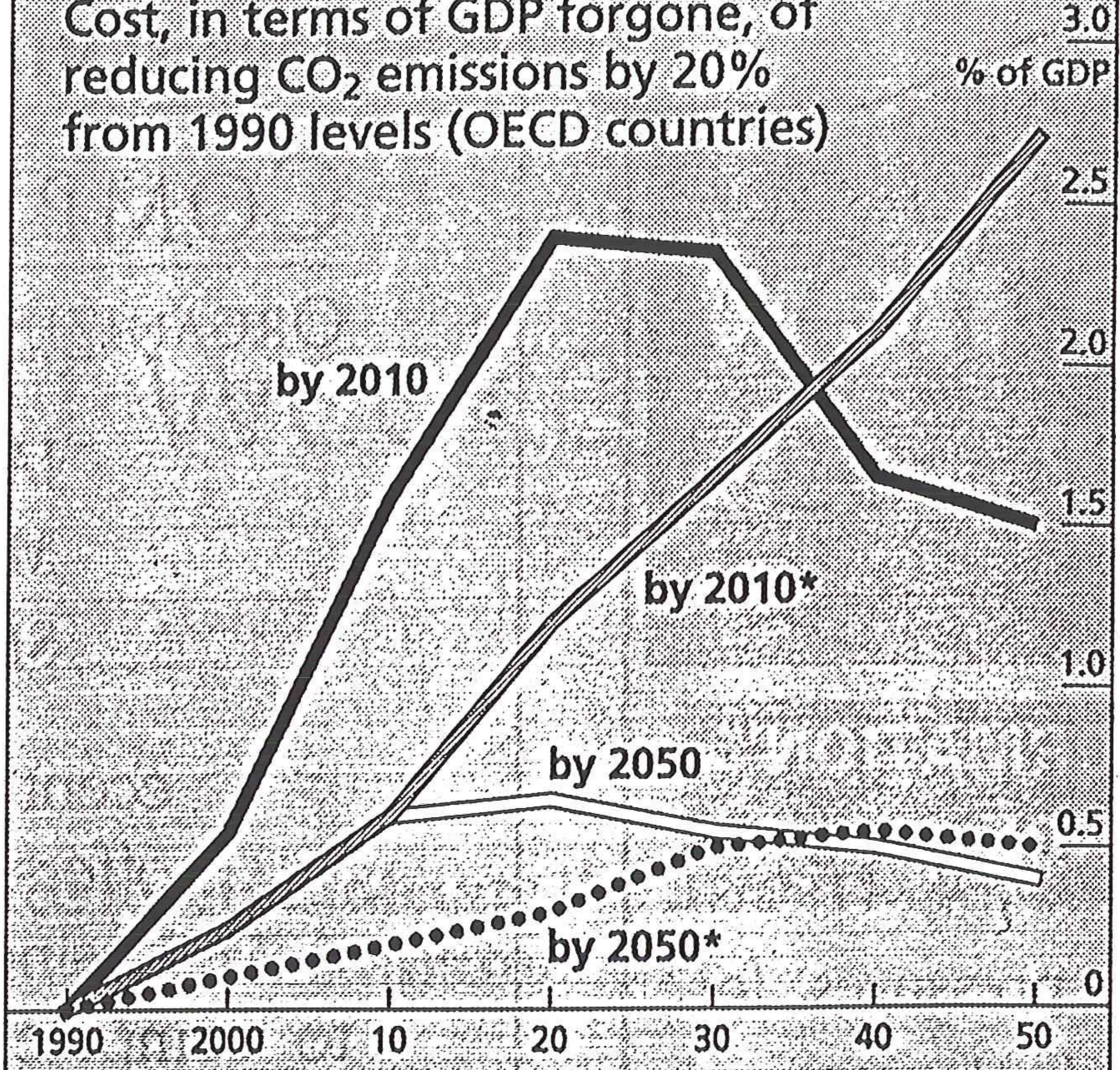
The parties to the treaty are meeting in Bonn this week to try to negotiate a new, binding agreement that cuts emissions beyond 2000. The talks are supposed to conclude in December in Kyoto, Japan.

European nations, saying they are well on their way to achieving the target for 2000, are pressing for deeper cuts in emissions by 2010.

Emissions of carbon dioxide, the main heat-trapping gas, increased to record levels in all five sectors that the Government report tracked: residential buildings, commercial buildings, industrial sites, transportation, and electricity generation.

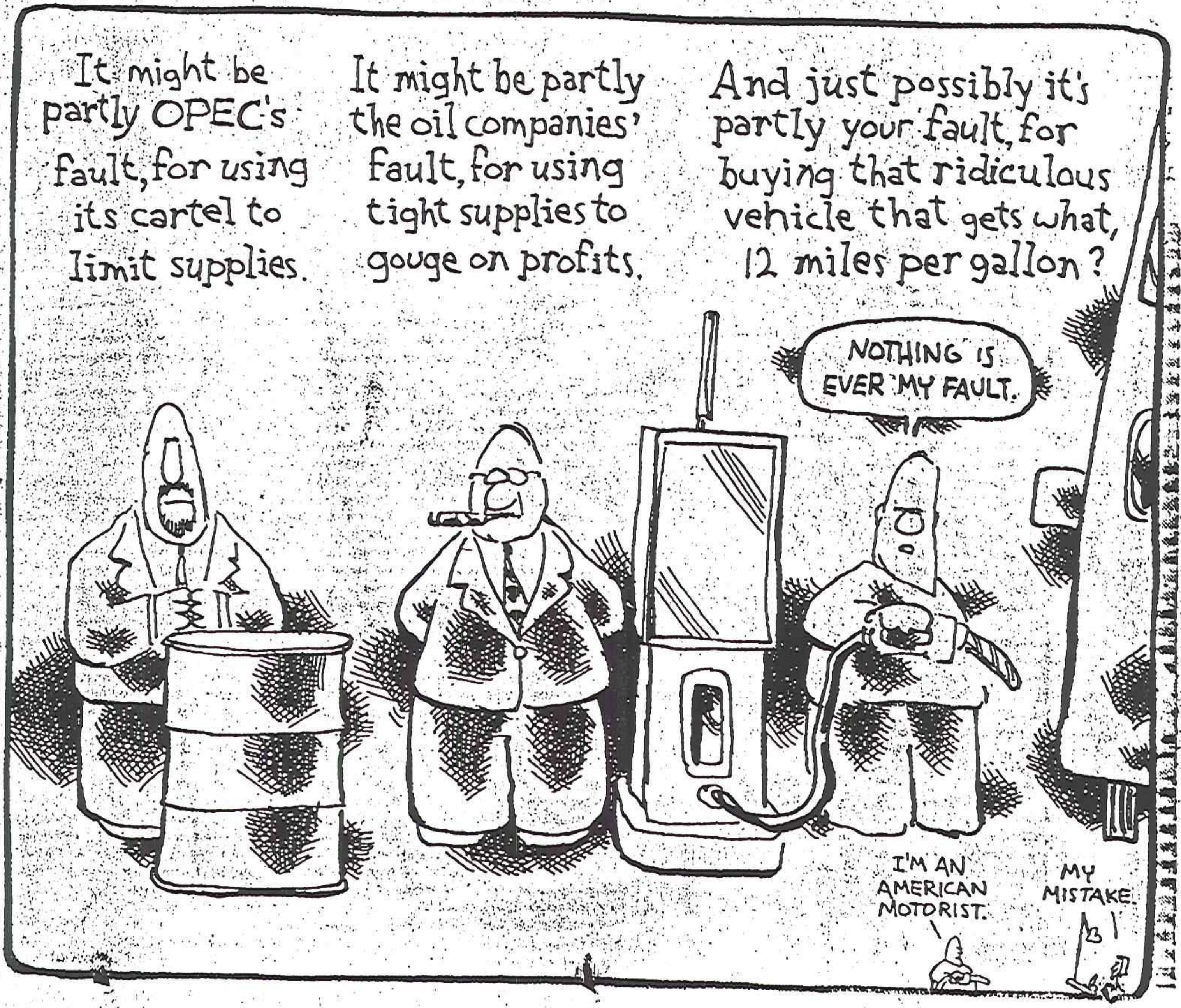
The kindest cuts

Cost, in terms of GDP forgone, of reducing CO_2 emissions by 20% from 1990 levels (OECD countries)

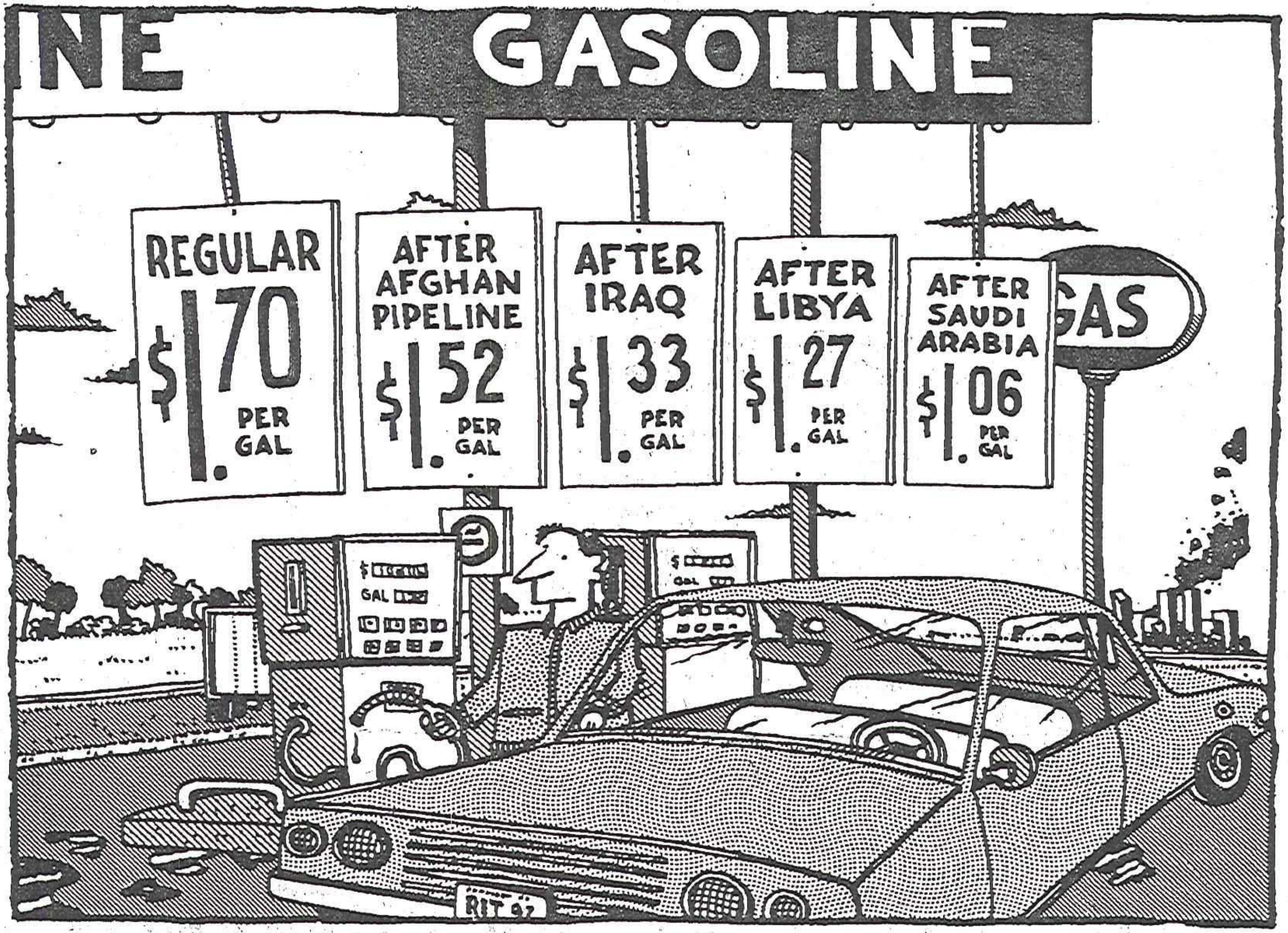


*Including "buying" cuts from non-OECD countries where this is more efficient

Source: OECD



Tom Toles
The Buffalo News
Universal Press Syndicate



Ted Rall
Universal Press Syndicate

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

By ALLEN R. MYERSON

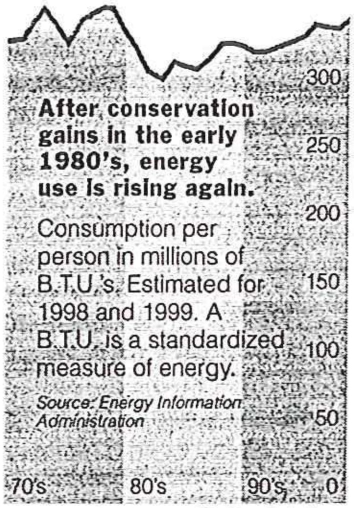
ARVADA, Colo. — Twenty-five years after an oil embargo proved that fuel supplies were neither reliable nor endlessly cheap, the United States has given up almost all the gains it made in conserving energy. On average, Americans have returned to consuming nearly as much energy as ever before.

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.



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.

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-

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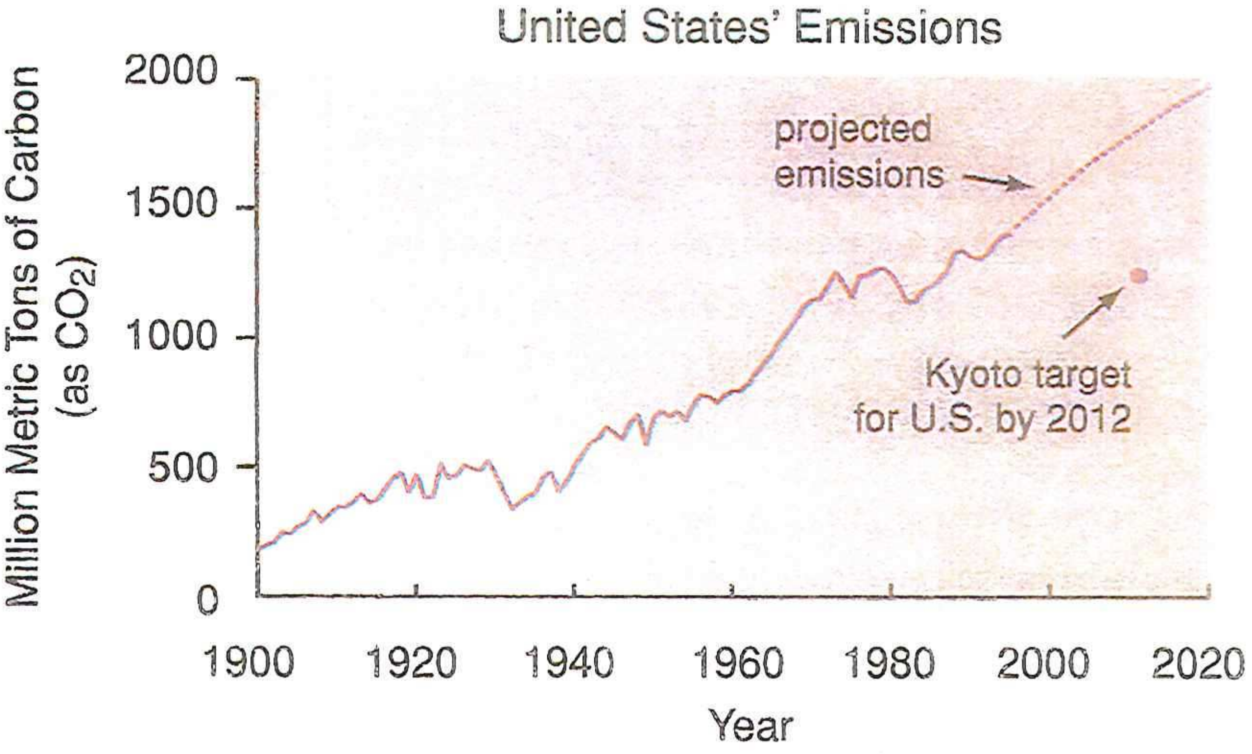
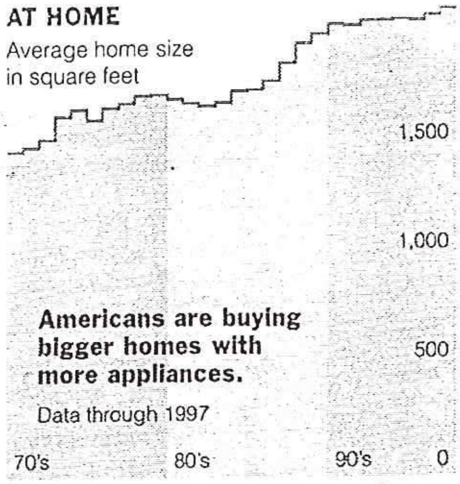

United States' Emissions
Million Metric Tons of Carbon (as CO_2)
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000
2020
Year
projected emissions
Kyoto target for U.S. by 2012

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.

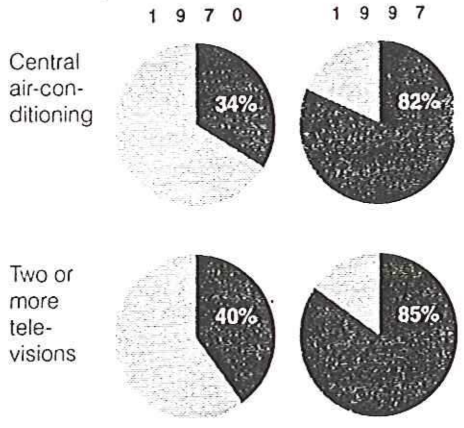
AT HOME


Average home size in square feet

Americans are buying bigger homes with more appliances.

Data through 1997

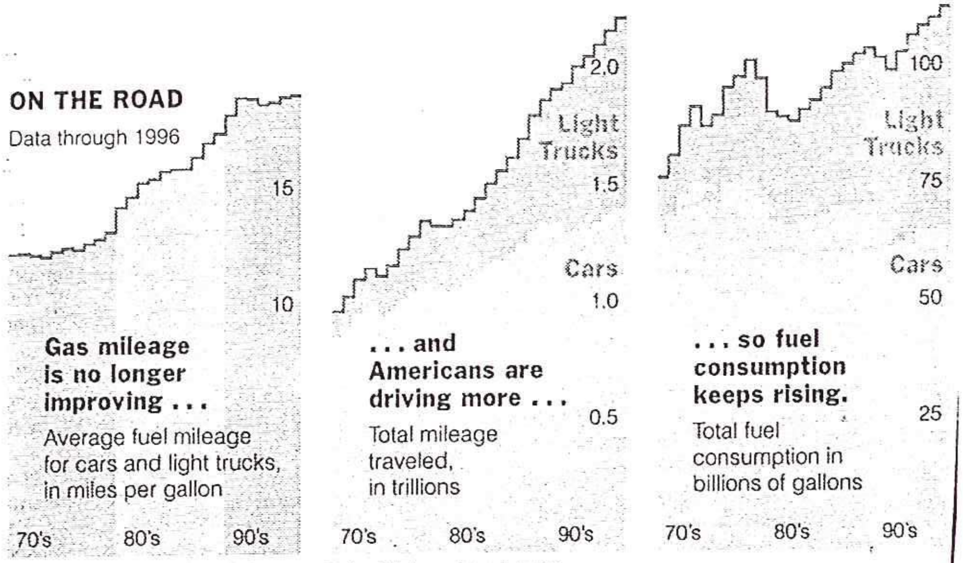
Percentage of homes with ...



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

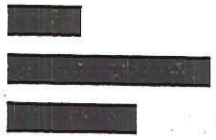
The New York Times

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

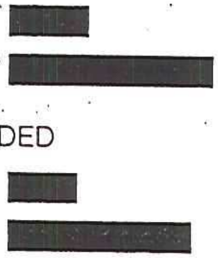
U.S. cents per kilowatt-hour in 1996



U.S.	8.4¢
Europe*	23.0
Japan	14.7

Cost of gasoline

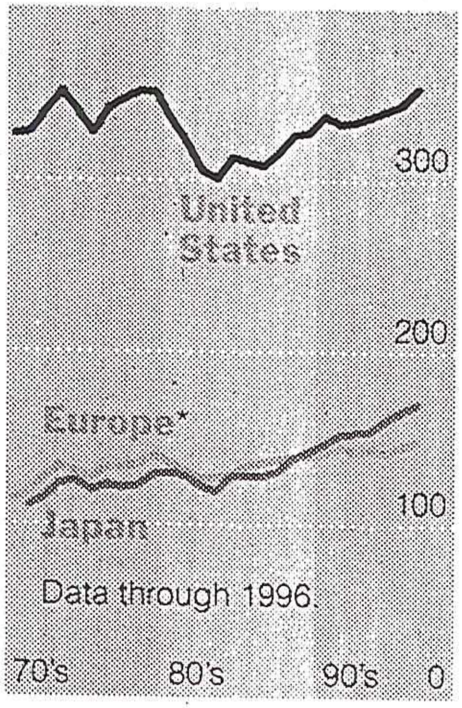
U.S. dollars per gallon in 1997



PREMIUM UNLEADED	
U.S.	$1.42
Europe*	3.65
REGULAR UNLEADED	
U.S.	$1.23
Japan	3.27

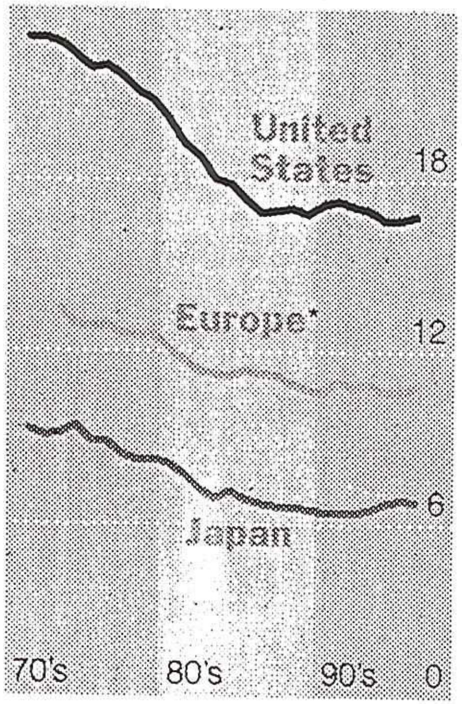
Energy use per person

Millions of B.T.U.'s



Energy use per dollar of G.D.P.

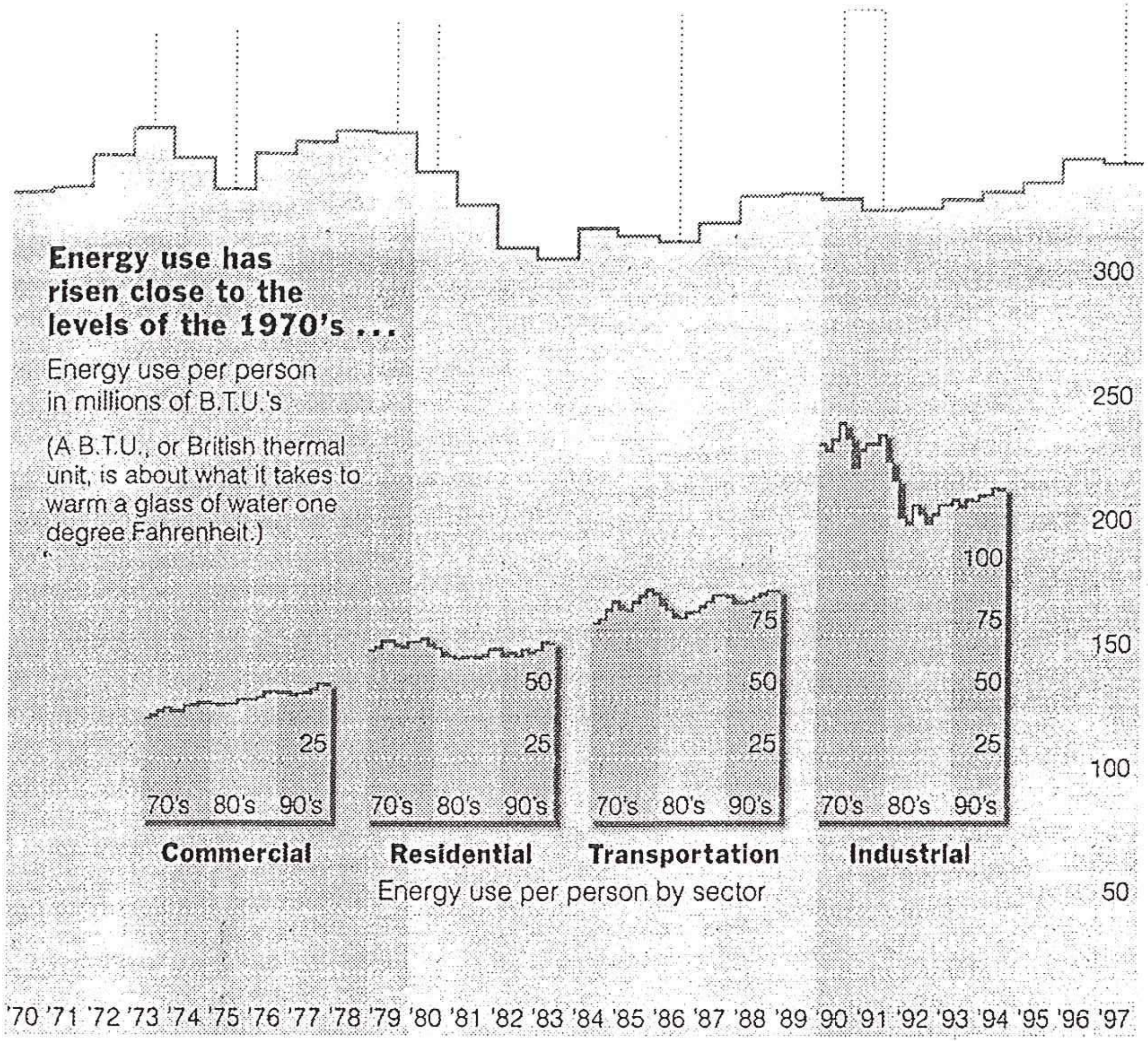
Thousands of B.T.U.'s per 1997 dollar



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

Source: Energy Information Administration

The New York Times

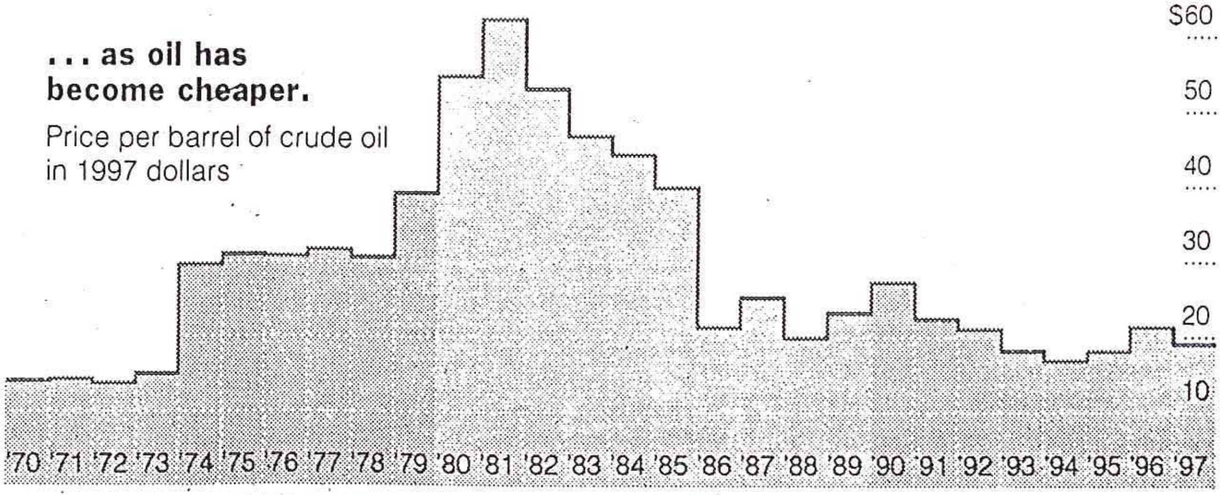


Energy use has risen close to the levels of the 1970's . . .

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

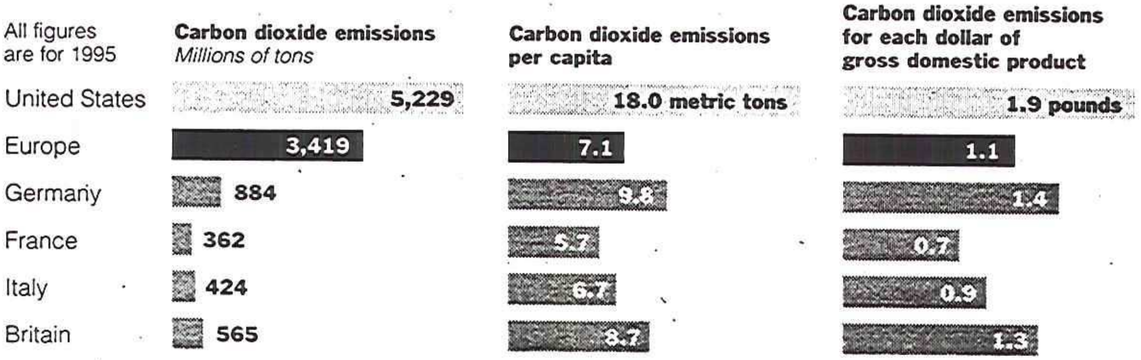
Sources: Cambridge Energy Research Associates; Energy Information Administration; American Petroleum Institute

The New York Times

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.

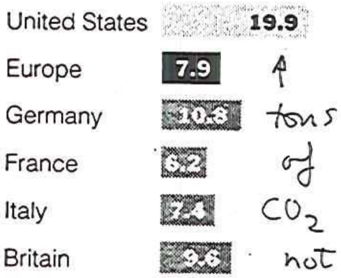
$$kg\,C = \frac{12}{12+16+16} \times kg\,CO_2$$

The New York Times

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

↑ tons of CO_2 not C

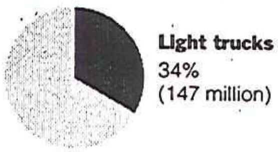
Source: International Energy Agency

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.

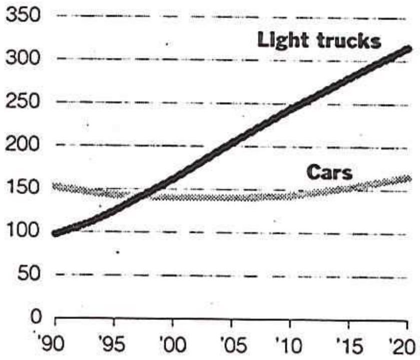
Light trucks are expected to account for 34 percent of the increase in total energy-related carbon emissions from 1990 to 2010. That total will be 32 percent higher than the 1990 level.

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

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

6 tons C / person – yr

= 1.5 GtC/yr total

= 27% of world emissions

why ?

One reason is the infatuation of US drivers with the SUV

Light truck emissions growing at 7% / yr

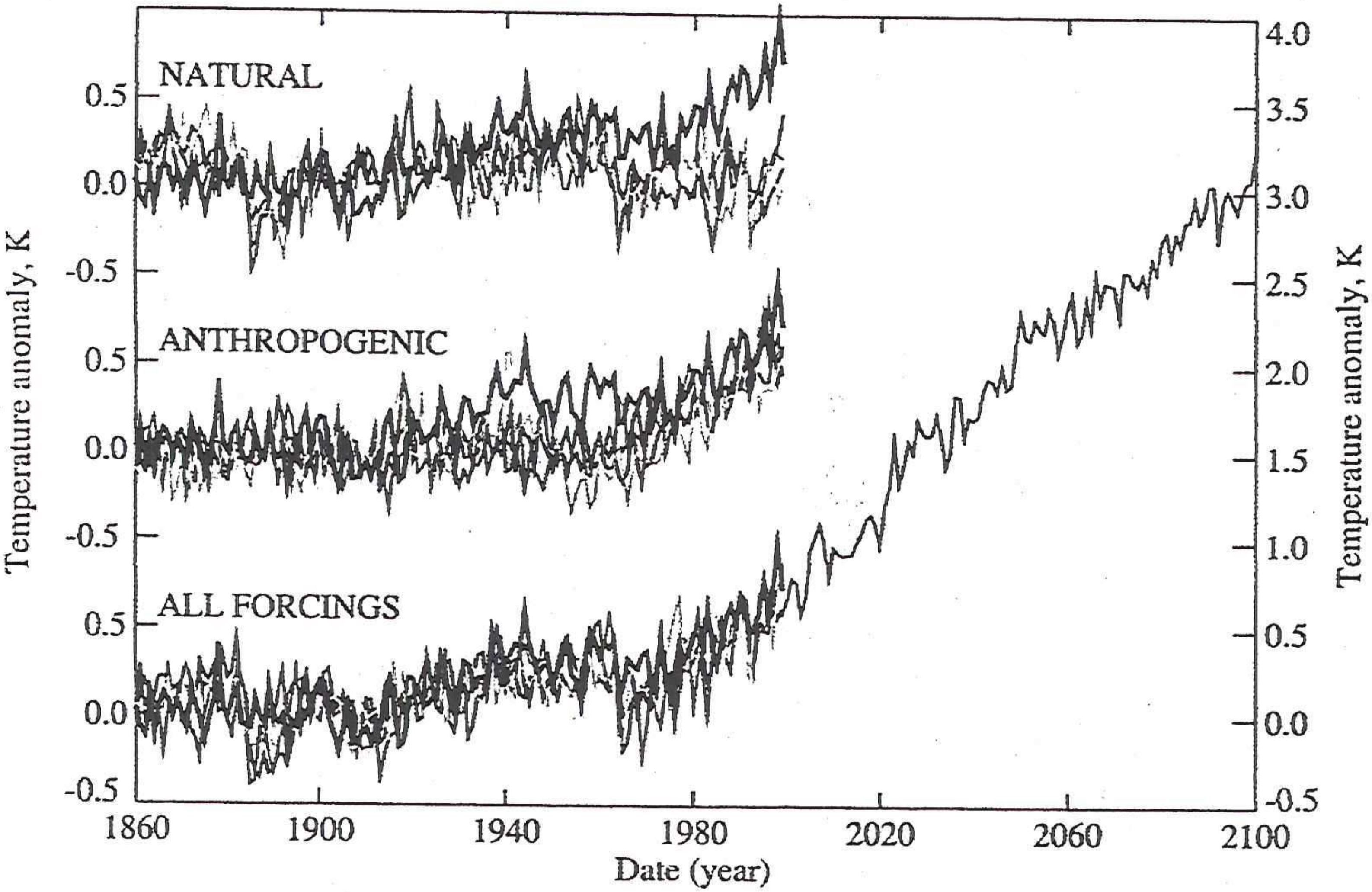


Fig. 1. Annual-mean global mean near-surface (1.5 m) temperature anomalies (relative to 1881–1920) for the NATURAL, ANTHRO, and ALL ensembles. Ensemble members are shown as colored lines, and observations [updated versions of surface temperature data set of Parker *et al.* (39)] are shown as a black line. All model data up to November 1999 are masked by the observational missing data mask and expressed, like the observations, as anomalies relative to 1961–1990. Future model data are masked by observational mask for year December 1998 to November 1999. Global means are then calculated and expressed as anomalies relative to 1881–1920.

BY THE NUMBERS

Carbon Emissions

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

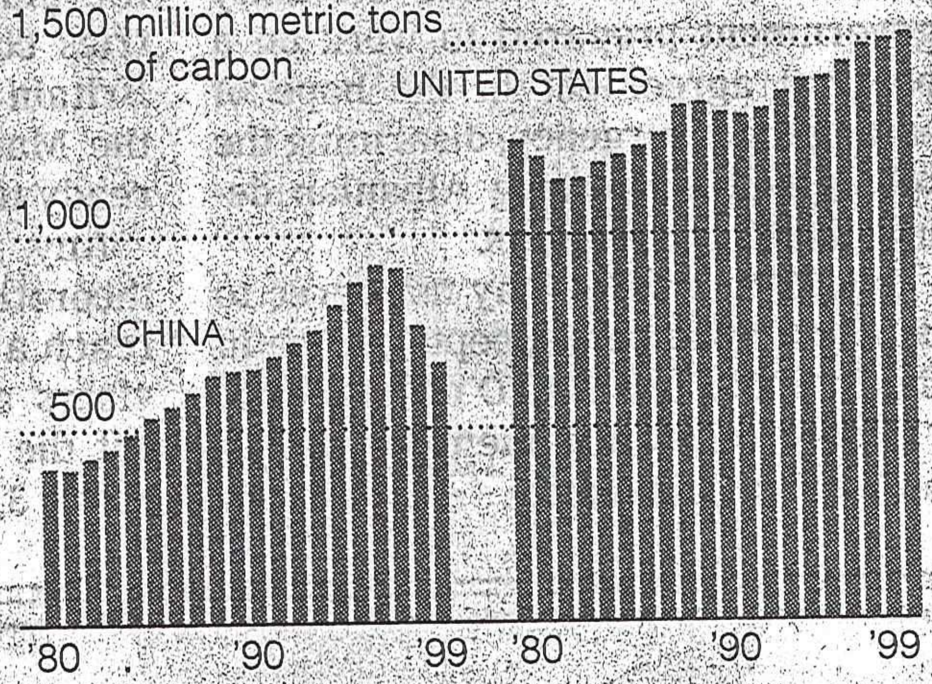
Metric tons of carbon per capita

Source: Carbon Dioxide Information Analysis Center

The New York Times

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

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.

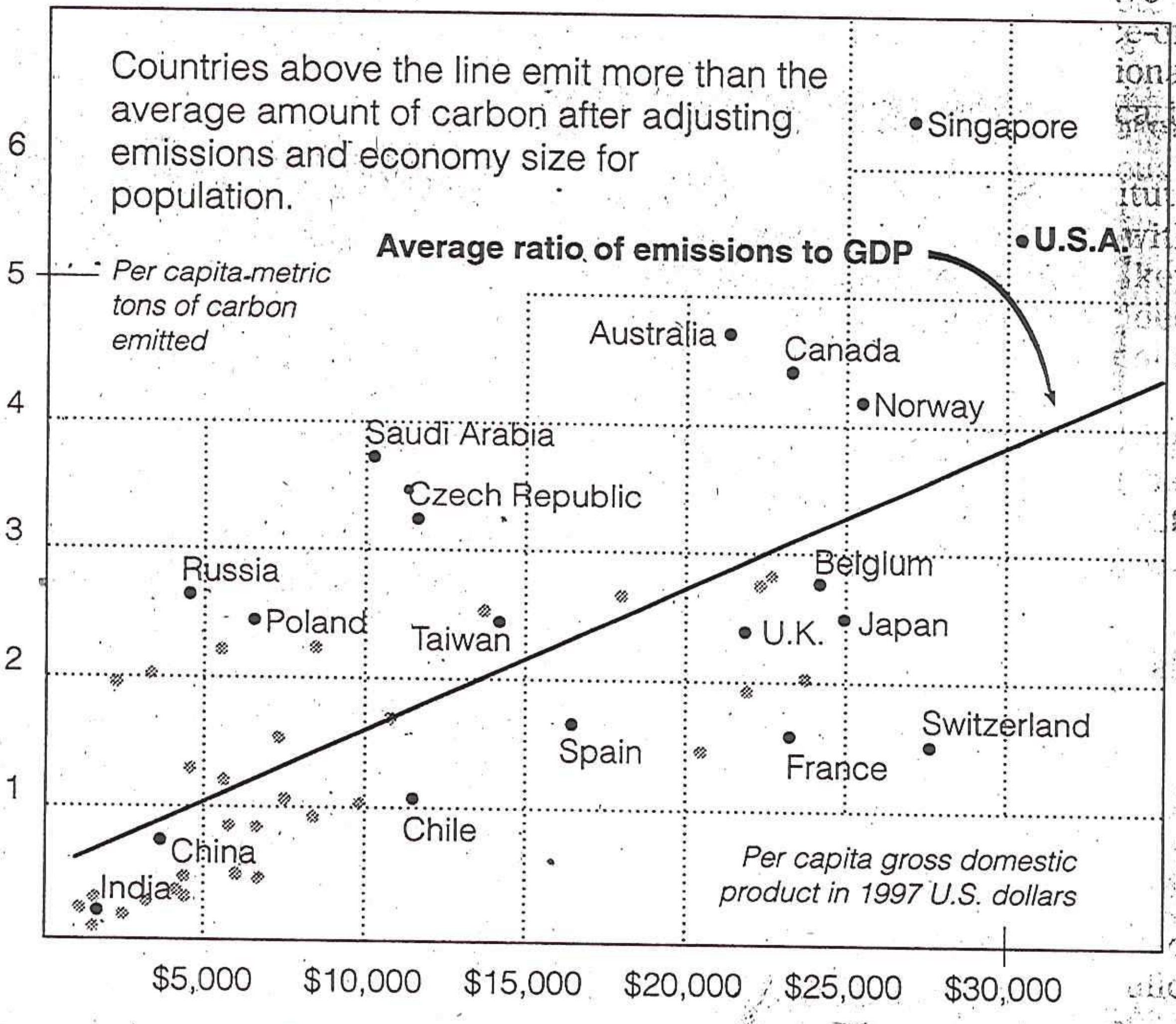
But when G.D.P. and emissions are measured and compared on a per capita basis, the playing field suddenly gets much more mixed, with Singapore, Australia, and Saudi Arabia joining the United States in the group with far above average output of carbon dioxide, while other counties prove more efficient 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



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

James Bronzan/The New York Times

Times

Late Edition
New York: **Today**, hazy, hot and humid, high 93. **Tonight**, muggy, low 77. **Tomorrow**, hazy sunshine, late thunder possible, high 89. **Yesterday**, high 88, low 60. Weather map, Page D8.

$1 beyond the greater New York metropolitan area. 75 CENTS

178 NATIONS REACH A CLIMATE ACCORD; U.S. ONLY LOOKS ON

A Compromise to Curb Emissions Linked to Global Warming

By ANDREW C. REVKIN

BONN, July 23 — With the Bush administration on the sidelines, the world's leading countries hammered out a compromise agreement today finishing a treaty that for the first time would formally require industrialized countries to cut emissions of gases linked to global warming.

The agreement, which was announced here today after three days of marathon bargaining, rescued the Kyoto Protocol, the preliminary accord framed in Japan in 1997, that was the first step toward requiring cuts in such gases. That agreement has been repudiated by President Bush, who has called it "fatally flawed," saying it places too much of the cleanup burden on industrial countries and would be too costly to the American economy.

Today, his national security adviser, Condoleezza Rice, said in Rome, where the president met with the pope, "I don't believe that it is a surprise to anyone that the United States believes that this particular protocol is not in its interests, nor do we believe that it really addresses the problem of global climate nge." She reiterated that the nt had created a task forc with atives

tougher emissions goals. Those countries now account for close to half of the emissions. The agreement now moves to a complex ratification process that calls for approval from the biggest polluting countries, which can be achieved even with United States opposition.

Officials from the European Union exulted over the compromise. Olivier Deleuze, the energy and sustainability secretary of Belgium, said there were easily 10 things in the final texts that he could criticize. "But," he said, "I prefer an imperfect agreement that is living than a perfect agreement that doesn't exist."

The Kyoto accord calls for the 38 industrialized countries by 2012 to reduce their combined annual gas emissions to 5.2 percent below levels measured in 1990. It set a different, negotiated target for each, with Ja-

Continued on Page A11

Average U.S. Car Is Tipping Scales At 4,000 Pounds

By DANNY HAKIM

DETROIT, May 4 — Detroit was recently ranked as the nation's most obese city by Men's Fitness magazine. Perhaps it is no surprise, then, that the Motor City's chief product is also losing the battle of the bulge.

The average new car or light-duty truck sold in the 2003 model year tipped the scales at 4,021 pounds, breaking the two-ton barrier for the first time since the mid-1970's, according to a report released by the Environmental Protection Agency last week.

The fattening of the nation's automobiles is a principal reason that average fuel economy has stopped improving and the nation's consumption of crude oil has been swelling: all else being equal, moving more weight takes more energy. Add in the additional pollutants and greenhouse gases released by burning more fuel, and it is not surprising that the upsizing trend is condemned by environmental groups.

But ranged against them in an increasingly bitter debate are industry lobbyists and conservative groups who argue that girth is good, for crashworthiness and because people want more space and power, though Honda is a notable dissenter in the industry.

At the center of the debate is the Bush administration's proposed rewriting of national fuel economy regulations. Though work on the plan is still in its early stages, one important aspect of it could lead automakers to make their vehicles even heavier on average. Environmentalists are distressed by the plan, but it has not been embraced by the auto industry, either.

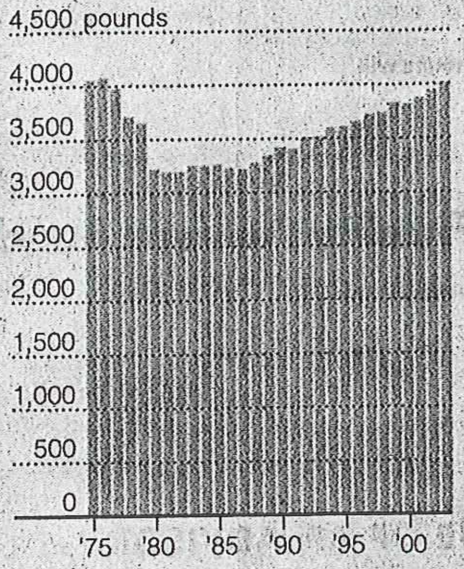
In recent months, the National Highway

Continued on Page 4

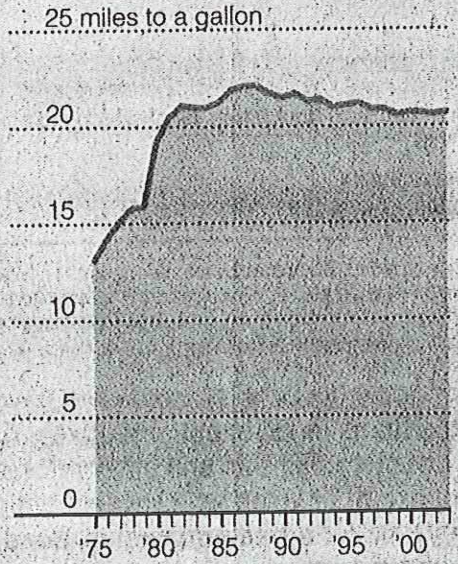
Bulking Up

For the first time in 25 years, the average weight of new vehicles was more than two tons last year. In recent years, as vehicles have gotten heavier, average fuel economy has declined.

AVERAGE LIGHT VEHICLE WEIGHT

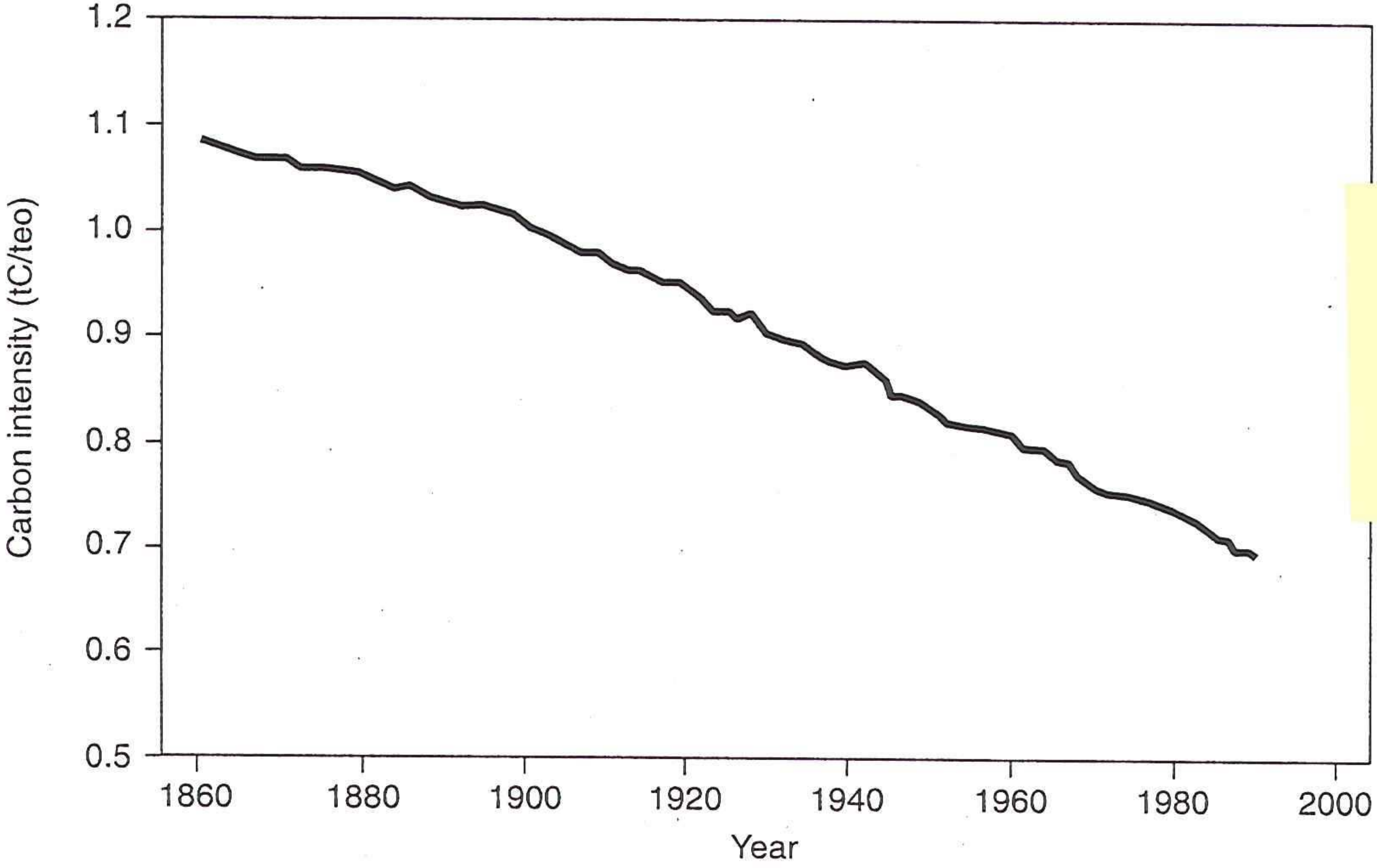


AVERAGE FUEL ECONOMY



Source: Environmental Protection Agency

The New York Times



extra

FIGURE 5.5 Carbon intensity of global energy consumption (tC/toe—tons of carbon per tons of oil equivalent).

Source: Nakicenovic (1997).

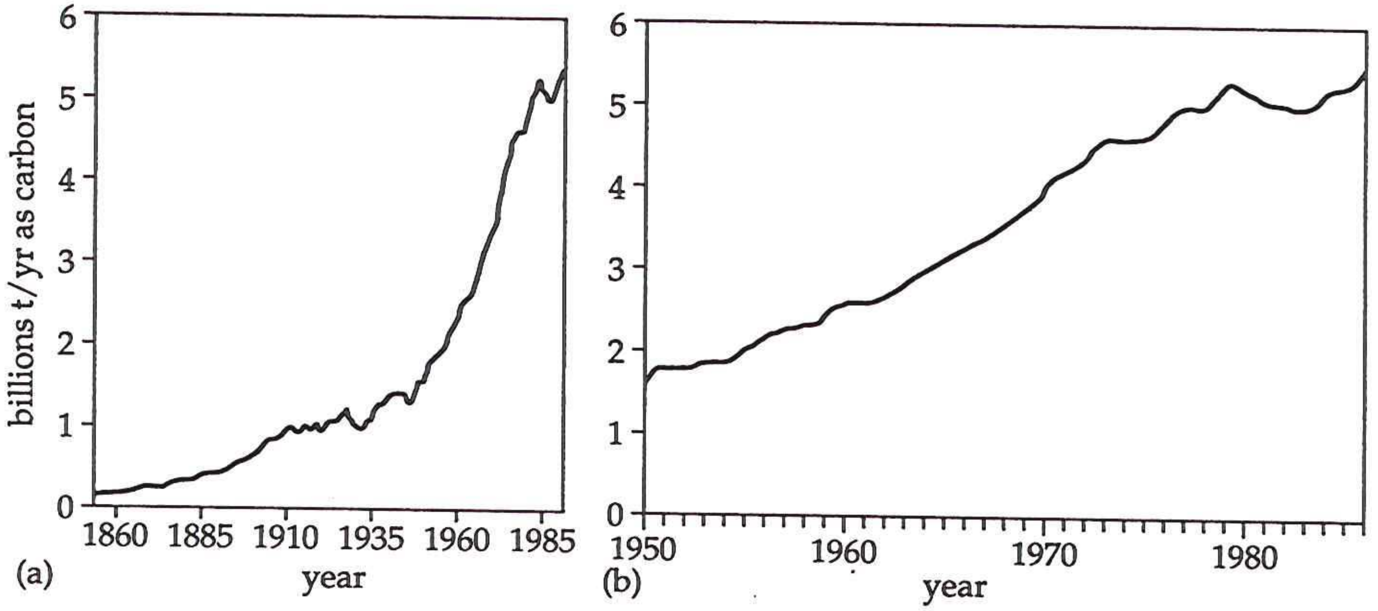


Figure 1.3 CO_2 emissions due to fossil fuel combustion (a) since 1860, (b) since 1950. (Data from UNEP 1991.)

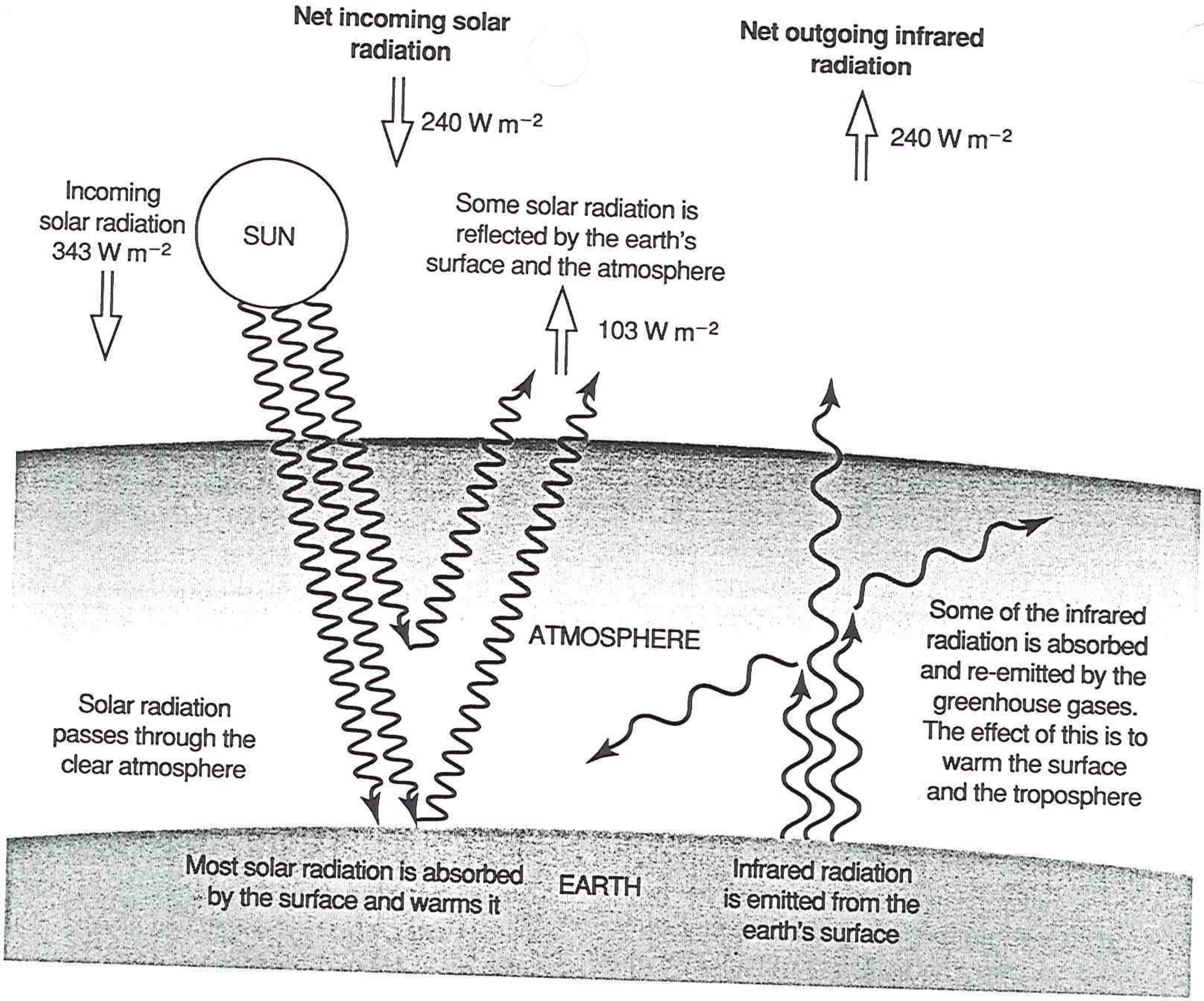


Figure 1: A simplified diagram illustrating the global long-term radiative balance of the atmosphere. Net input of solar radiation (240 Wm^{-2}) must be balanced by net output of infrared radiation. About a third (103 Wm^{-2}) of incoming solar radiation is reflected and the remainder is mostly absorbed by the surface. Outgoing infrared radiation is absorbed by greenhouse gases and by clouds keeping the surface about 33 °C warmer than it would otherwise be.

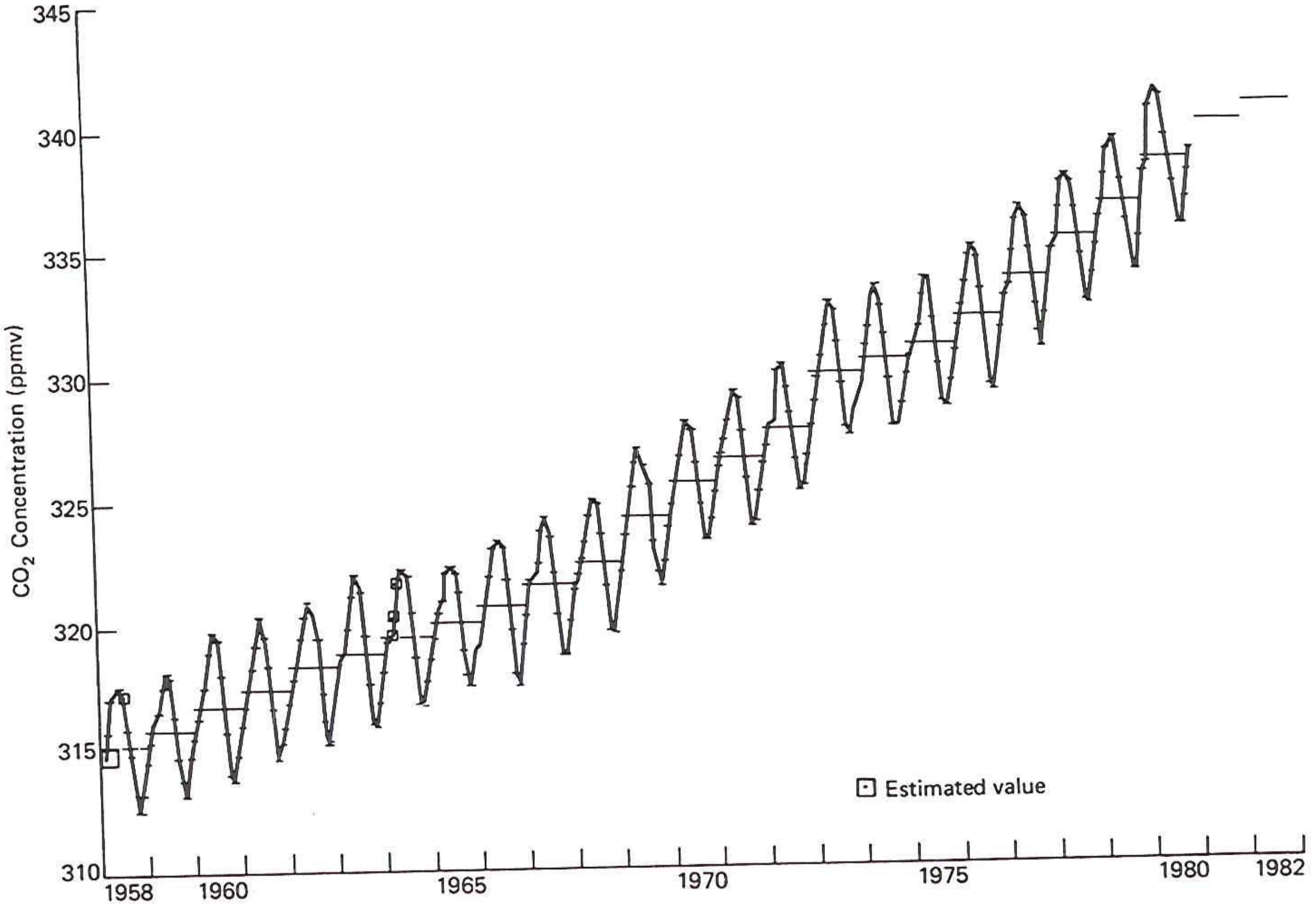
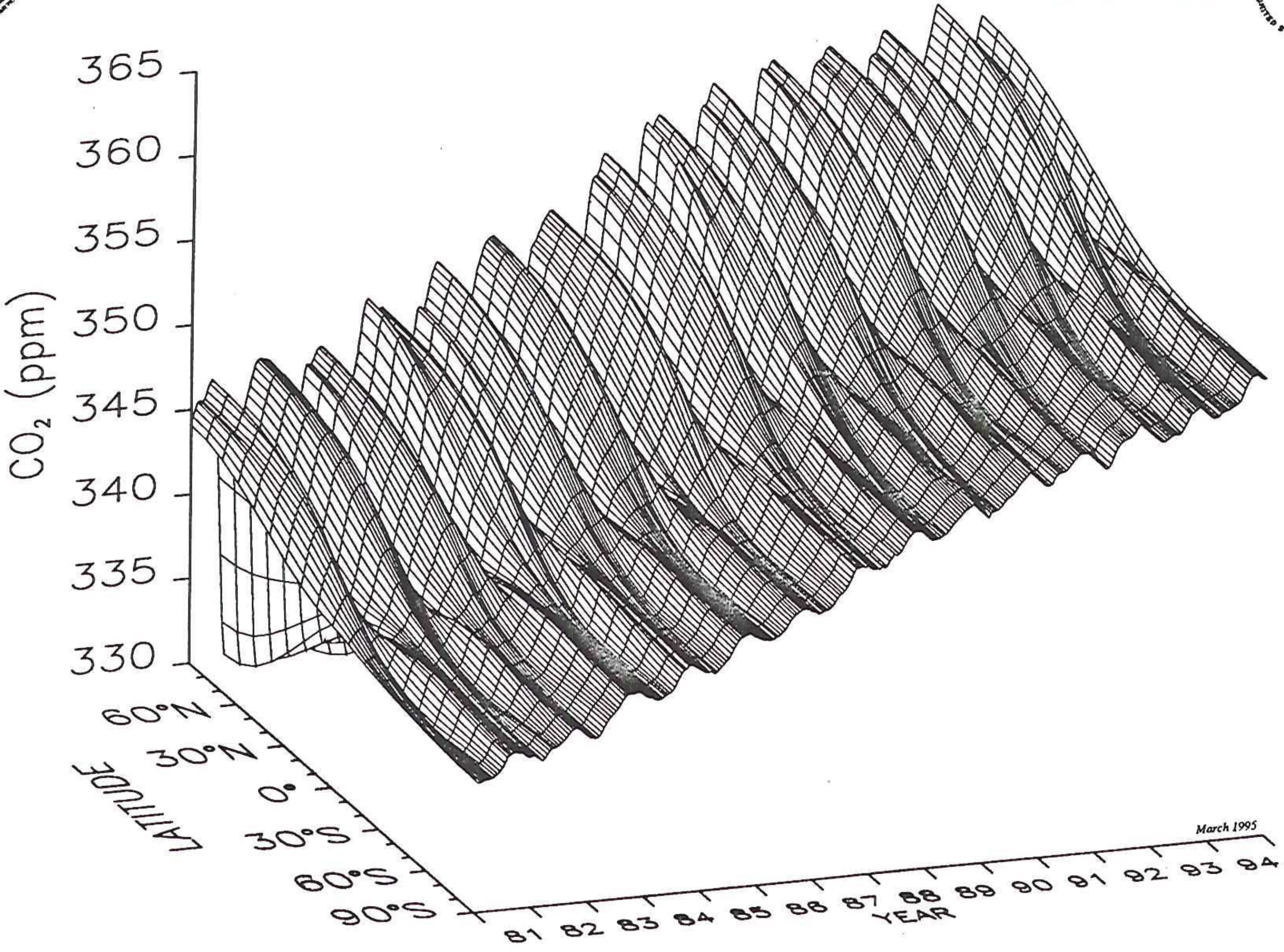


Figure 2.16 Mean monthly concentrations of atmospheric CO_2 at Mauna Loa, Hawaii. The horizontal bar represents the mean annual concentration of CO_2 for each year. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the Northern Hemisphere. (Note 1 ppmv CO_2 = 2.12 Gt C, where 1 Gt C = 10^9 tons C). (After NRC 1983, based on measurements of C. D. Keeling and the National Oceanic and Atmospheric Administration. Average annual CO_2 concentrations for 1981 and 1982 from Komhyr et al. 1985.)

GLOBAL DISTRIBUTION OF ATMOSPHERIC CARBON DIOXIDE



March 1995

Three dimensional representation of the global distribution of atmospheric carbon dioxide in the marine boundary layer assuming no variation with longitude. Data from the NOAA/CMDL Global Cooperative Air Sampling Network were used. The surface represents data smoothed in time and latitude. Principal investigators: Pieter Tans and Thomas Conway, NOAA/CMDL Carbon Cycle Group, Boulder, Colorado, (303) 497-6678.

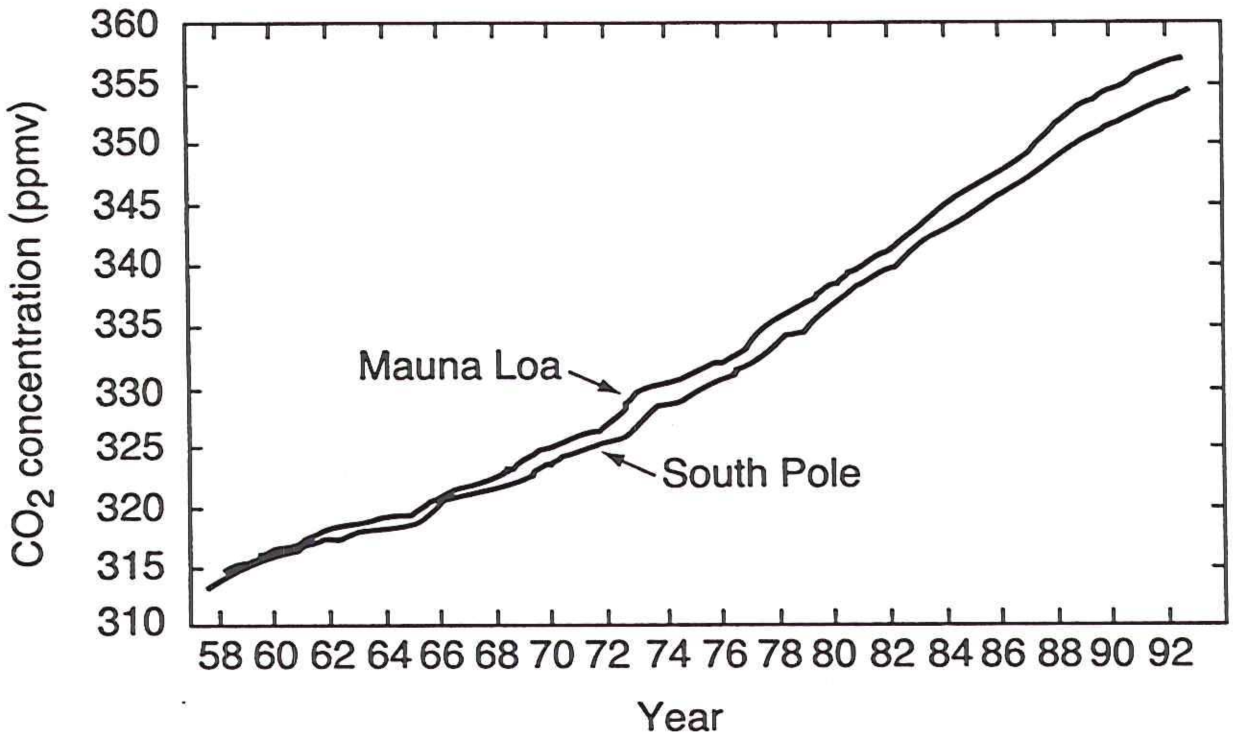


Figure 1.4: Trends in CO_2 concentration and the growing difference in concentration between the Northern and Southern Hemispheres.

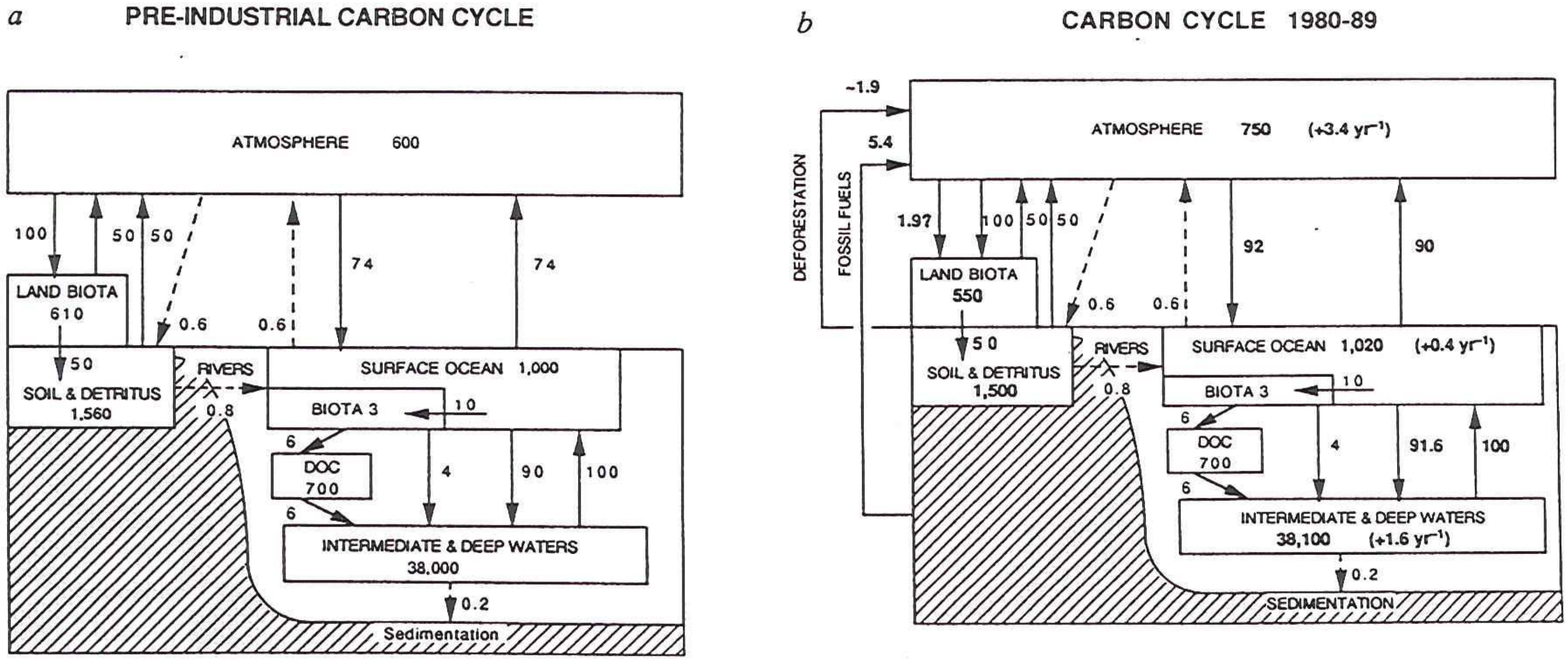


FIG. 1 Global carbon cycle reservoirs and fluxes, in Gt C and Gt C yr^{-1}, respectively (1 Gt C$=10^{15}$ g C). *a*, Reconstructed pre-industrial situation and *b*, present-day situation. In *b*, bold numbers denote fluxes or reservoir sizes which have changed due to human activities. The numbers in *b* correspond approximately to those given in the 1990 IPCC assessment[2] with the following exceptions: an oceanic pool of dissolved organic carbon (DOC) is included (E. Peltzer, personal communication). The marine biological new production (equal to particles plus DOC exported from the surface) is 10 Gt C yr^{-1}, taken from model calculations[65,66]. The indicated transport by water circulation is much larger than in the IPCC assessment[2], but this is primarily a matter of definition. The IPCC downward flux of 35 Gt C yr^{-1} corresponds roughly to global deep-water formation (~46×10^6 m^3 s^{-1}). Our upward flux (100 Gt C yr^{-1}) is chosen such that it is about ten times the total new production, which in a 2-box model yields a surface water ΣCO_2 deficit of 10%, as observed. Our fluxes therefore represent exchange between the surface and a depth of perhaps 1 km where most of the particles and DOC have been remineralized. The cumulative land-use effect, assumed to be −120 Gt C, is divided equally between vegetation and soils. The difference between river input and sedimentation has been closed by fluxes of 0.6 Gt C yr^{-1} from ocean to atmosphere and from atmosphere to biota (dashed arrows).

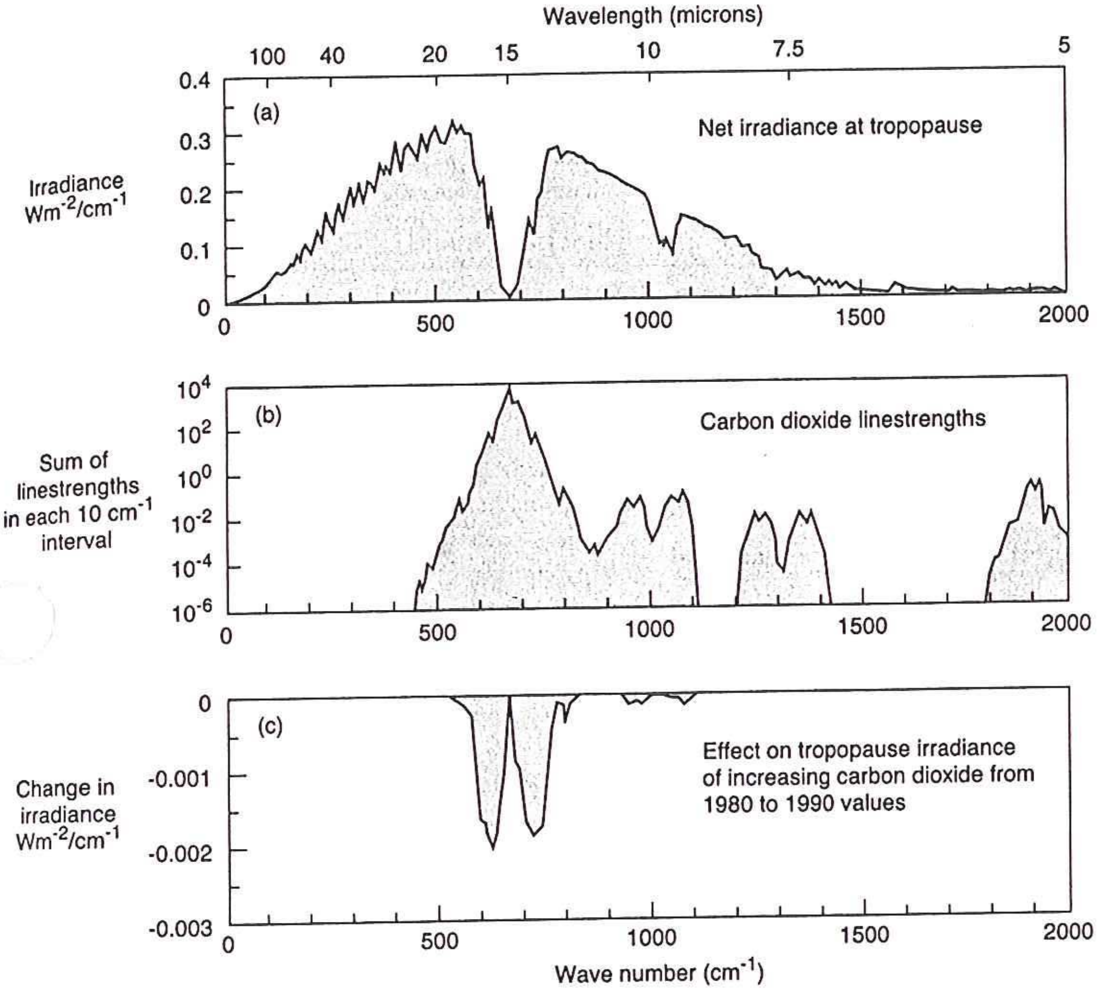
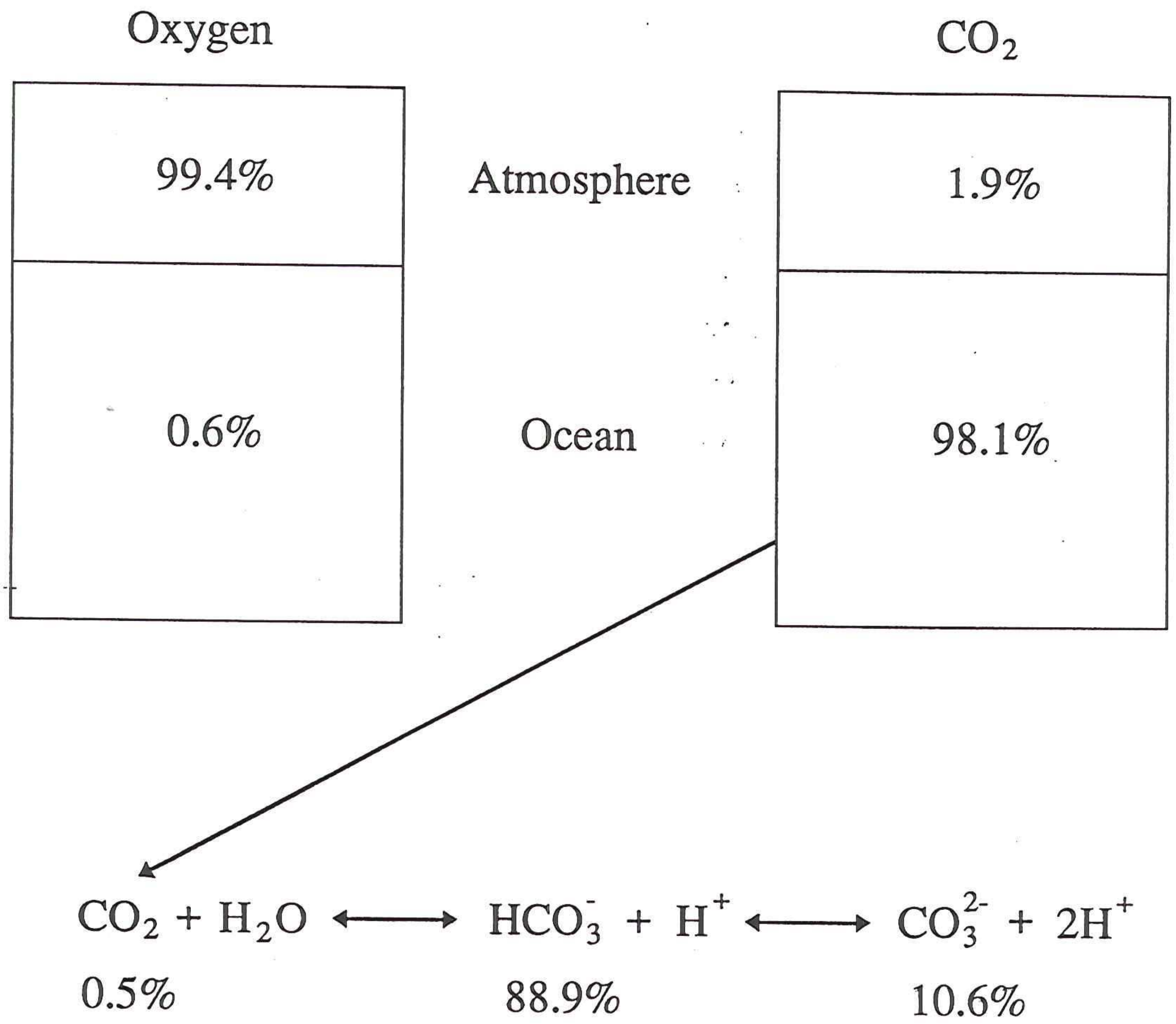


Figure 4.1: An illustration that additional amounts of CO_2 in the atmosphere do enhance the greenhouse effect – the details of the calculations are given in the footnote to the box. (a) Net infrared irradiance (Wm^{-2}/cm^{-1}) at the tropopause from a standard radiative transfer code using typical atmospheric conditions; (b) Representation of the strength of the spectral lines of CO_2 in the thermal infrared; note the logarithmic scale. (c) Change in net irradiance at the tropopause (in Wm^{-2}/cm^{-1}) on increasing the CO_2 concentration from its 1980 to 1990 levels, whilst holding all other parameters fixed. Note that the change in irradiance at the wavelength of maximum absorption, as shown in (b), is essentially zero, while the most marked effects on the irradiance are at wavelengths at which CO_2 is less strongly absorbing.


Oxygen
CO_2
99.4%
Atmosphere
1.9%
0.6%
Ocean
98.1%
$CO_2 + H_2O \longleftrightarrow HCO_3^- + H^+ \longleftrightarrow CO_3^{2-} + 2H^+$
0.5%
88.9%
10.6%

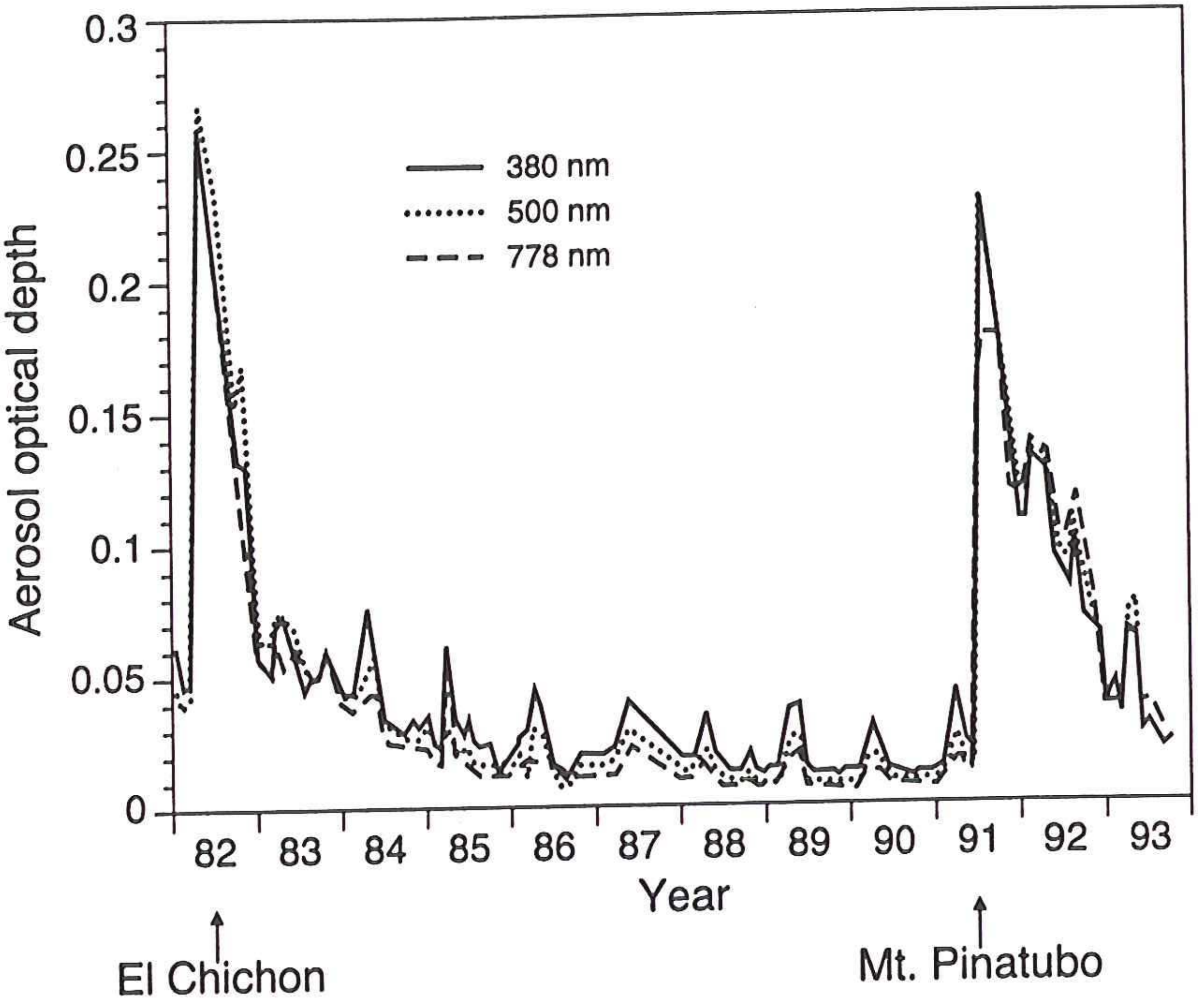


Figure 3.6: Variation of aerosol optical depth following the Mt. Pinatubo and El Chichon eruptions (from Dutton and Christy, 1992), showing the removal of aerosol over several years following the eruptions.

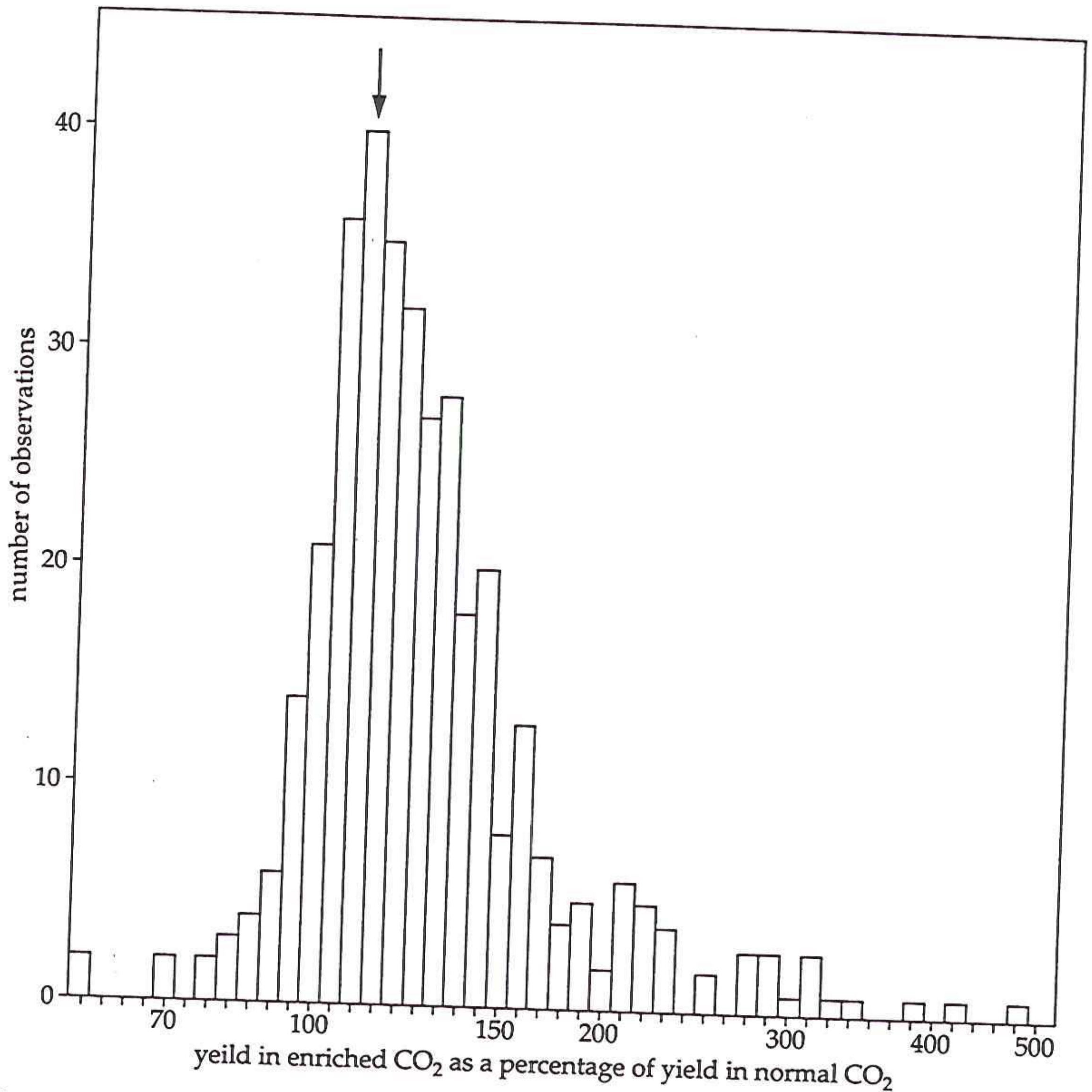


Figure 5.1 This diagram collects together a large number of observations on how growing in enriched atmospheric CO_2 affects crop yield. The most common observation (indicated by the arrow) is that yield is enhanced by 30%, but in many cases the yield increase was higher. It is also interesting to note that in a very few cases there was a decrease in yield. (After Kimball 1982.)

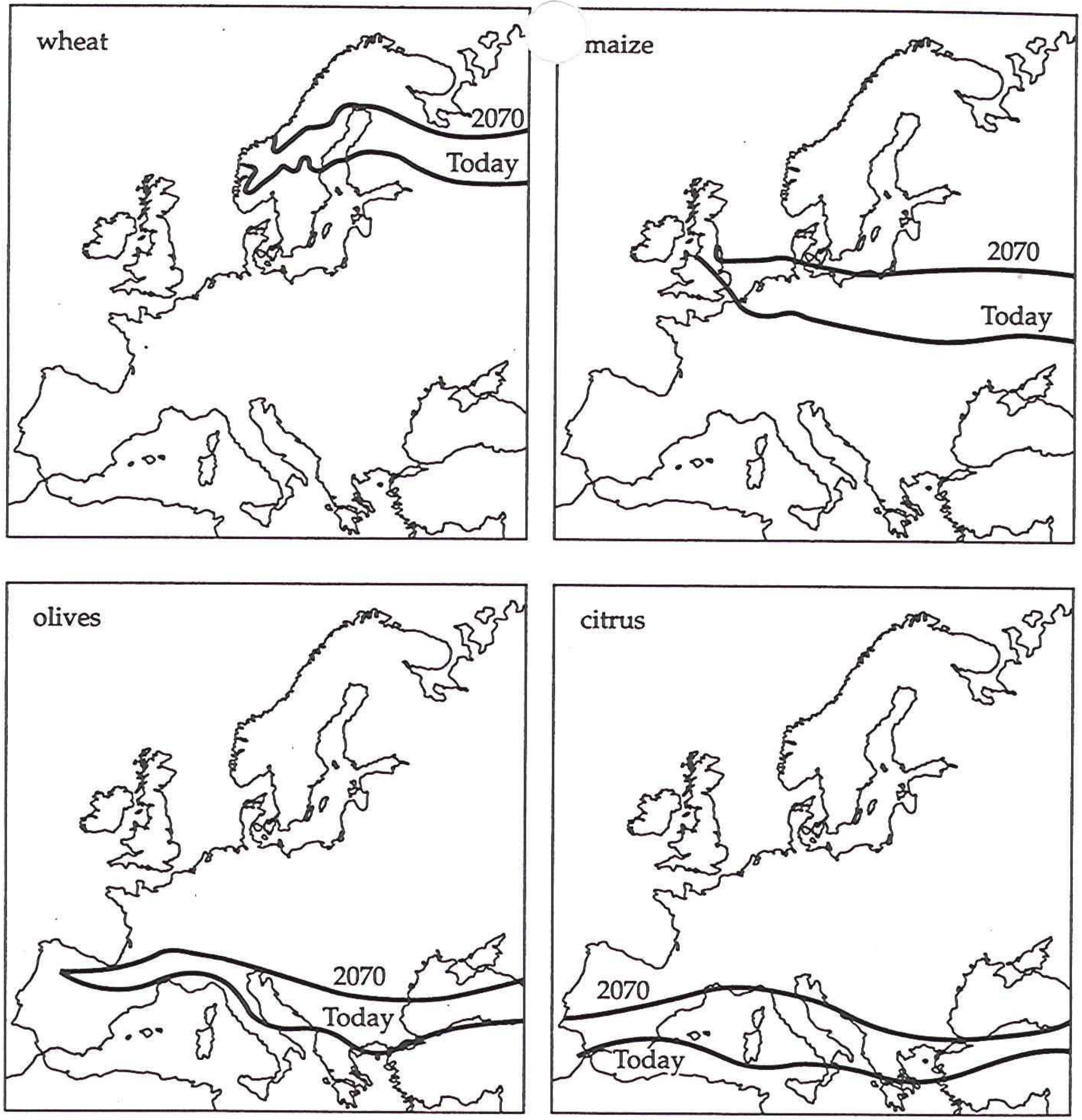


Figure 5.7 Predicted changes in the northern cropping boundary of four selected crops in Europe.

TABLE 6–1 Anthropogenic contributions to sea level rise over the past 100 years

Water reservoir	Present net extraction rate ($\times 10^{10}$ m^3 yr^{-1})	Sea-level rise rate (mm yr^{-1})	Estimated sea-level change to date (mm)
United States			
High plains	1.2	0.03	1.1
Southwest	1.0	0.03	0.92
California	1.3	0.04	1.2
Africa and Asia			
Sahara	1.0	0.03	0.56
Arabia	1.6	0.04	0.89
Aral (lake)			
1960	2.7	0.08	2.2
Aral (groundwater)	3.7	0.1	3.1
Caspian (lake)	0.77	0.02	1.3
Caspian (groundwater)	0.47	0.01	0.78
Sahel (soil water)	0.34	0.01	0.28
Worldwide			
Deforestation	4.9	0.14	3.4
Wetland reduction	0.2	0.006	1.3
Dams	–	–	–5.2
Total	19.2	0.54	11.8

After D. L. Sahagian, F. W. Schwartz, and D. K. Jacobs, 1994, *Nature,* v. 367, p. 54.

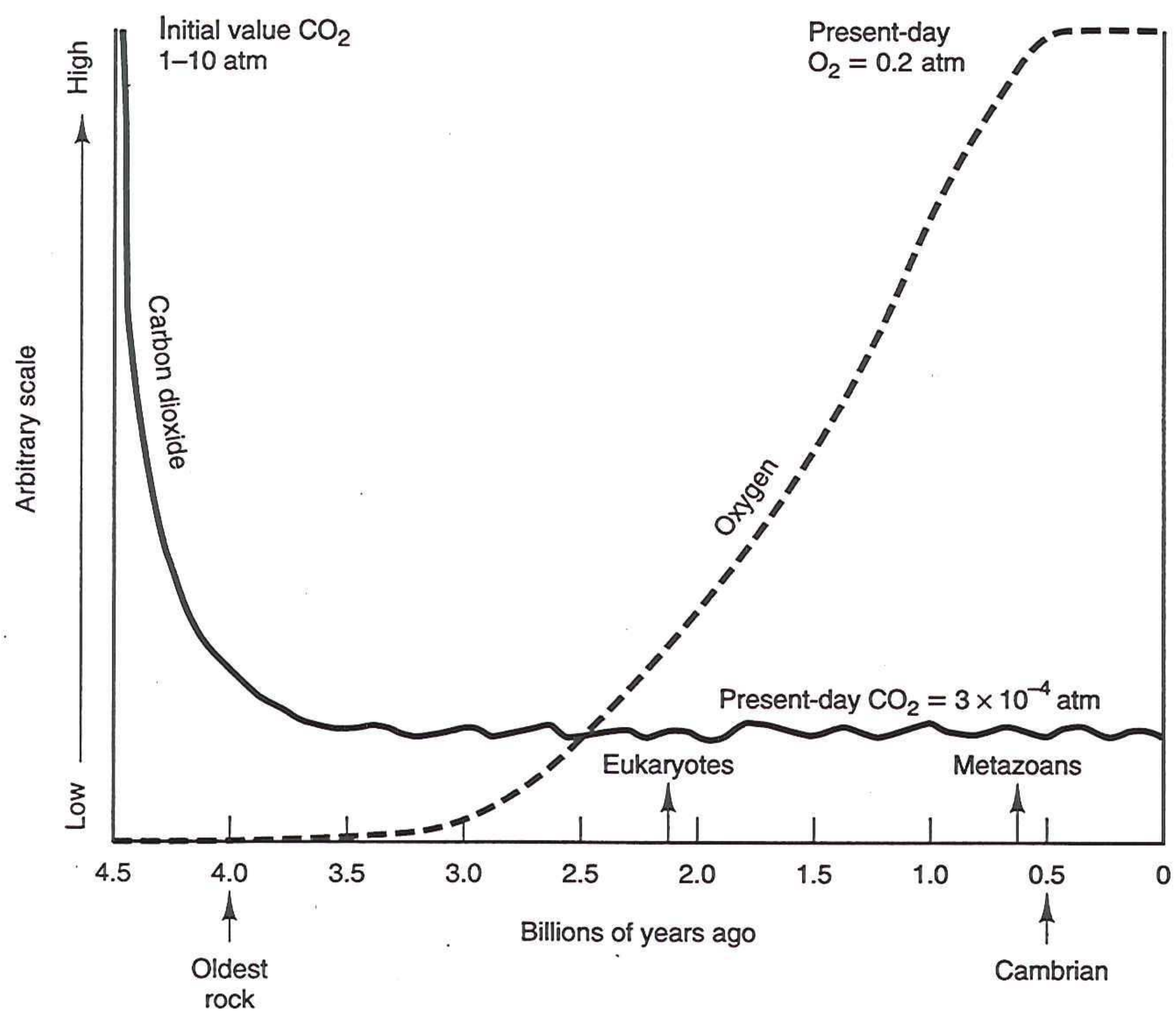
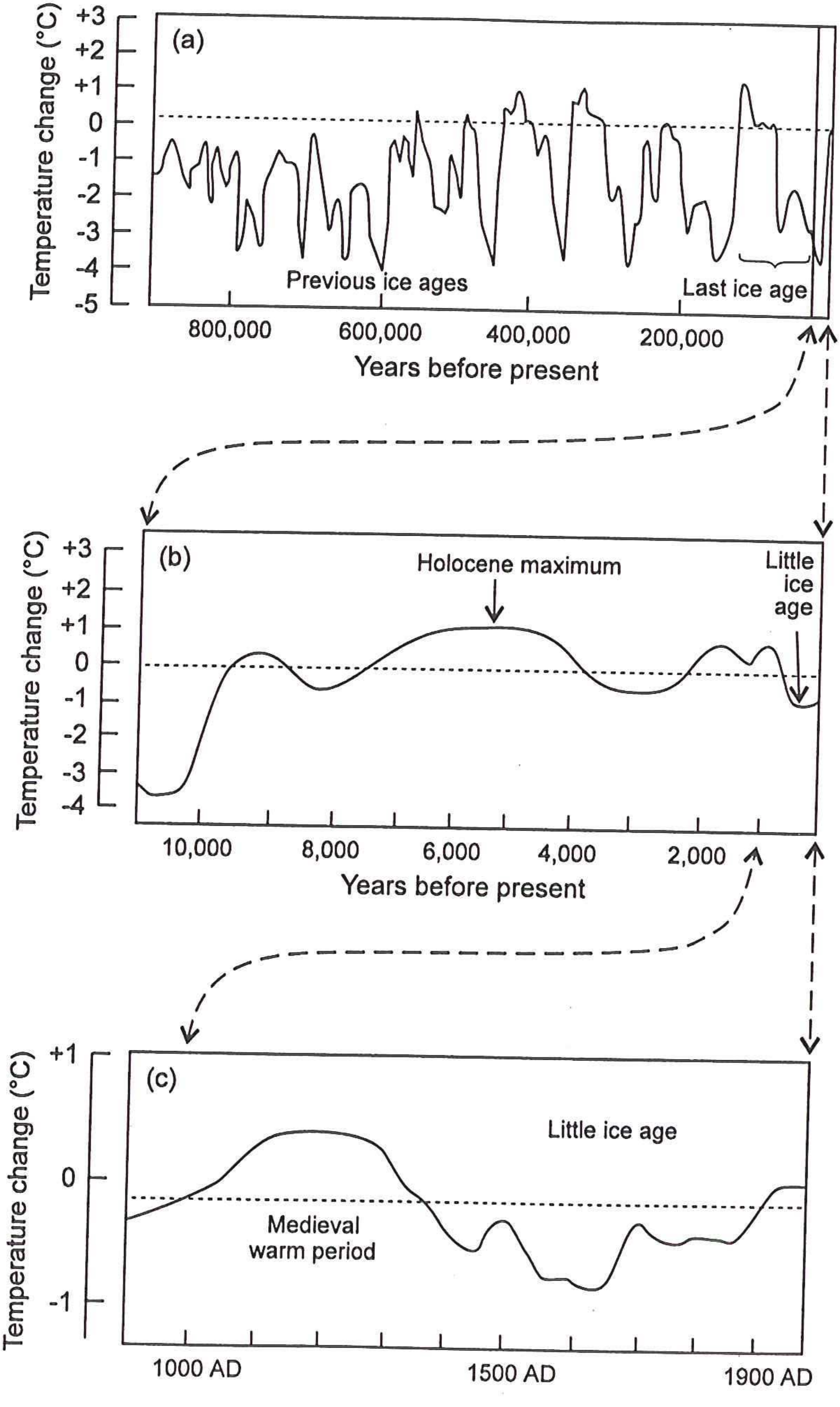


FIGURE 3–10 The history of oxygen and carbon dioxide in the atmosphere during Earth history.


(a)
Temperature change (°C)
+3
+2
+1
0
-1
-2
-3
-4
-5
Previous ice ages
Last ice age
800,000
600,000
400,000
200,000
Years before present
(b)
Temperature change (°C)
+3
+2
+1
0
-1
-2
-3
-4
Holocene maximum
Little
ice
age
10,000
8,000
6,000
4,000
2,000
Years before present
(c)
Temperature change (°C)
+1
0
-1
Little ice age
Medieval
warm period
1000 AD
1500 AD
1900 AD

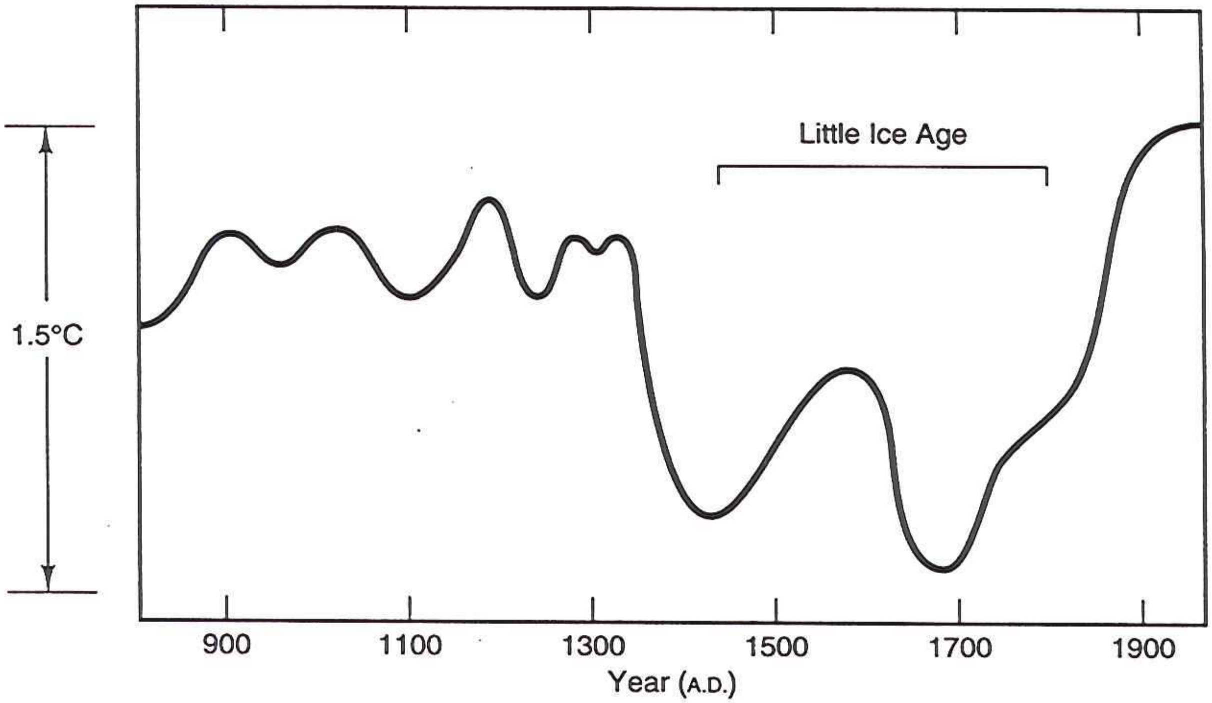


FIGURE 4–14 Climate of the past 1000 years. The graph is an estimate of winter conditions in Eastern Europe, as compiled from manuscript records. During the Little Ice Age (1450-1850 A.D.), mountain glaciers all over the world advanced considerably beyond their present limits. (Adapted from H. H. Lamb, 1969, by J. Imbrie and K. P. Imbrie, 1979, *Ice Ages,* Enslow Publishers.)

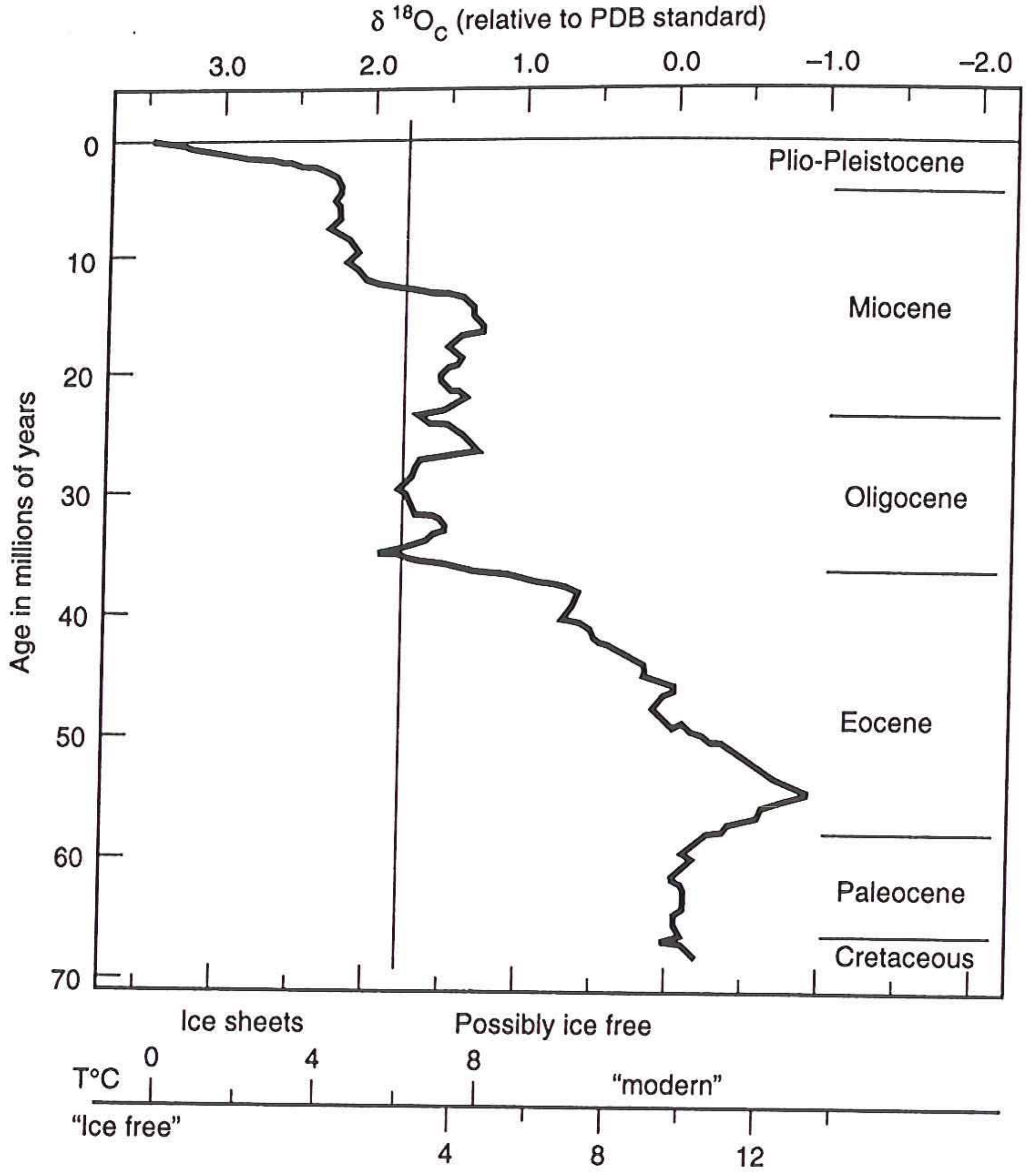


FIGURE 4–4 Composite curve of oxygen isotope data for Tertiary benthic foraminifera from the North Atlantic. The data can be transformed to ocean bottom temperature by setting the oxygen isotope composition of the ocean on an ice-free and ice-present (modern) basis. (From K. G. Miller, R. G. Fairbanks, and G. S. Mountain, 1987, *Paleoceanography,* v. 2, p. 1. Copyright by the American Geophysical Union.)

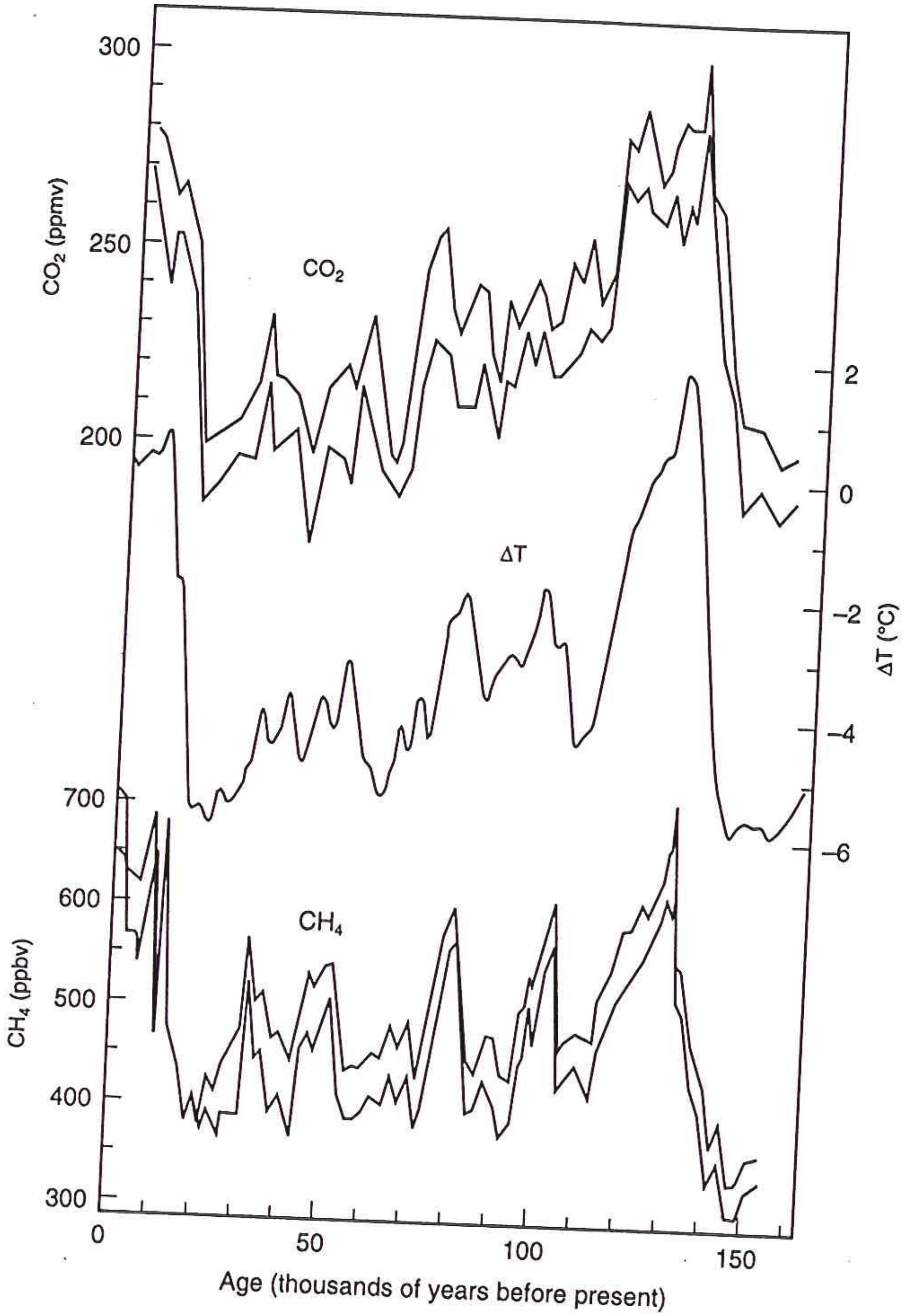


FIGURE 7–1 The variation of CO$_2$ and methane over time as inferred from an ice core (Vostok) from Antarctica (from J. M. Barnola, D. Raynaud, Y. S. Korotkevich, and C. Lorius, 1987, *Nature,* v. 329, p. 408, and J. Chappellaz, J. M. Barnola, D. Raynaud, and Y. S. Korotkevich, 1990, *Nature,* v. 345, p. 127.) The envelope for each curve represents the range of values observed for each period of time. The temperature is based on oxygen isotope studies of the ice (from C. Lorius, J. Jouzel, D. Raynaud, J. Hansen, and H. Le Treut, 1990, *Nature,* v. 347, p. 139.) (From *Climate Change*, 1990, Report of IPCC Working Group 1, Cambridge University Press.)

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]
Natural gas	14–15	14.5
Liquid fuels from crude oil	19–22	20.3
Bituminous coal	25	25.1
Shale oil	30–110	
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.

Out of the Tailpipe

The Clean Air Act of 1970 imposed tight controls on certain types of emissions but left others unregulated. As a result, progress in cutting pollution has been uneven.

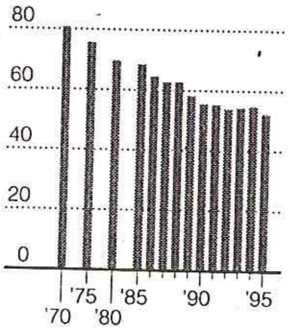
REGULATED EMISSIONS

While emissions of regulated pollutants have generally been dropping …

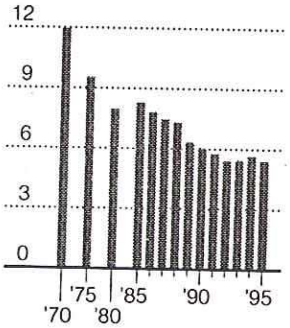
UNREGULATED

… carbon dioxide emissions keep rising.

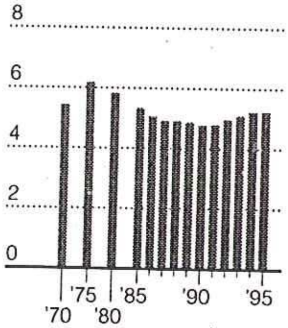
CARBON MONOXIDE
MILLIONS OF SHORT TONS FROM LIGHT-DUTY VEHICLES



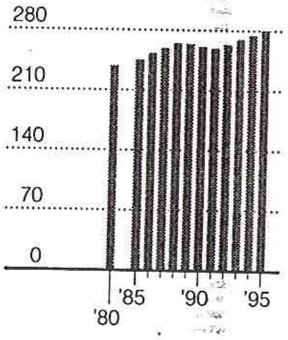
VOLATILE ORGANIC COMPOUNDS
MILLIONS OF SHORT TONS FROM LIGHT-DUTY VEHICLES



NITROGEN OXIDE
MILLIONS OF SHORT TONS FROM LIGHT-DUTY VEHICLES

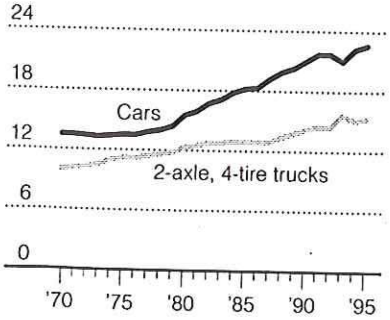


CARBON DIOXIDE
MILLIONS OF METRIC TONS FROM MOTOR GASOLINE

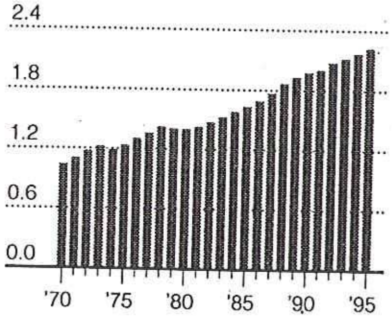


America's fleet of cars is more fuel efficient now because of another set of regulations; trucks are not covered by the rules, but have been made somewhat more efficient. The steady increase in the number of miles Americans drive, however, has swamped such improvements, driving up overall gas consumption.

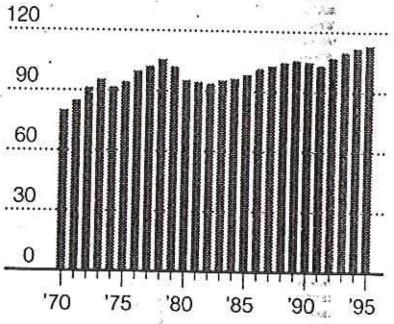
FUEL ECONOMY
MILES PER GALLON



TOTAL MILES TRAVELED EACH YEAR
TRILLIONS OF MILES



TOTAL FUEL CONSUMPTION
BILLIONS OF GALLONS



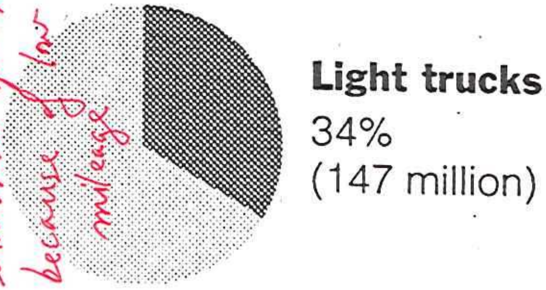
Sources: Office of Air Quality Planning and Standards, Environmental Protection Agency; Center for Transportation Analysis at the Oak Ridge National Laboratory

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.

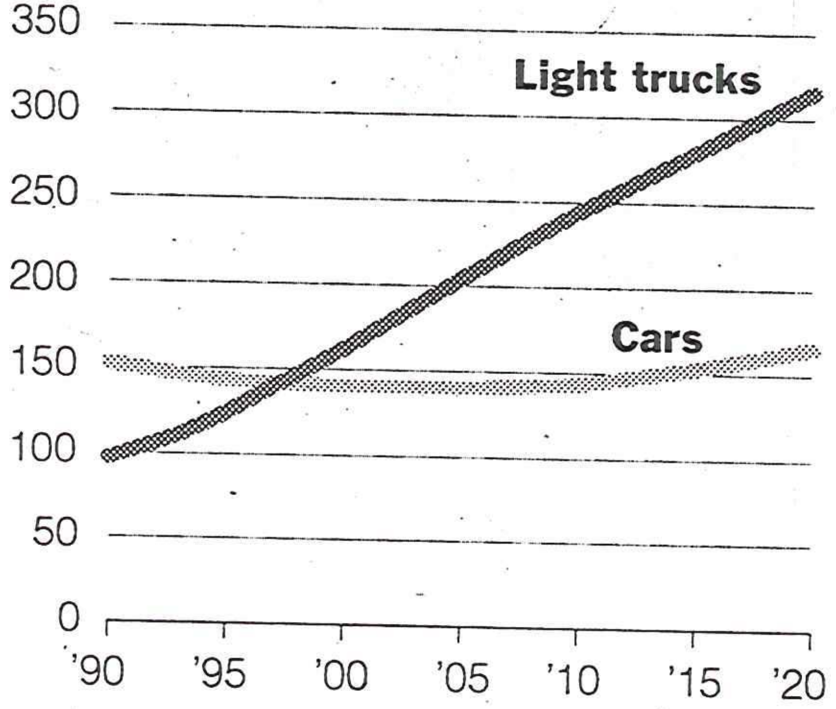
Total increase: 435 million metric tons



Total # of "light trucks" in US ≈ $\frac{1}{2}$ × # cars — but total CO_2 emission greater because of low mileage

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

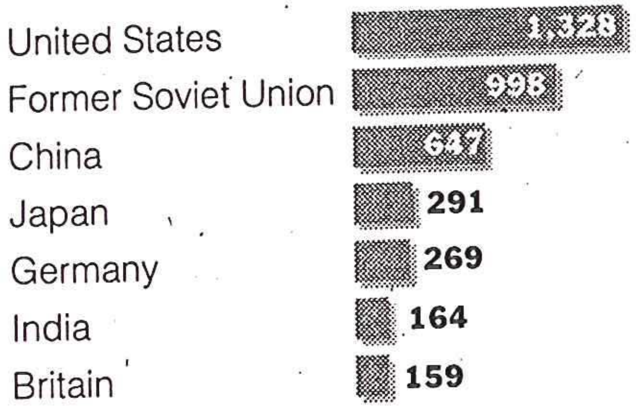
The New Y Times

Who Emits Most

The United States produces more heat-trapping gases than other countries, but it reaps a bigger economic benefit. Figures are for 1993.

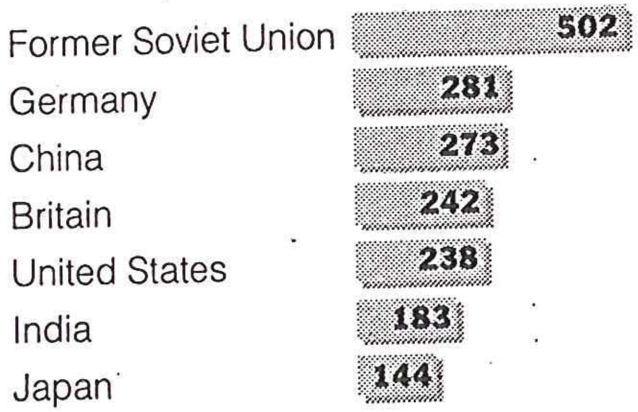
EMISSIONS OF CARBON GASES FROM ENERGY PRODUCTION

In millions of metric tons



CARBON EMISSIONS RELATIVE TO ECONOMIC ACTIVITY

*Metric tons of carbon emitted for each million dollars of gross domestic product**



*Gross domestic product figures are converted to dollars at rates that equalize purchasing power.

Source: Center for Clean Air Policy

CO_2 emissions from fossil fuel combustion (10^9 tonnes of carbon)

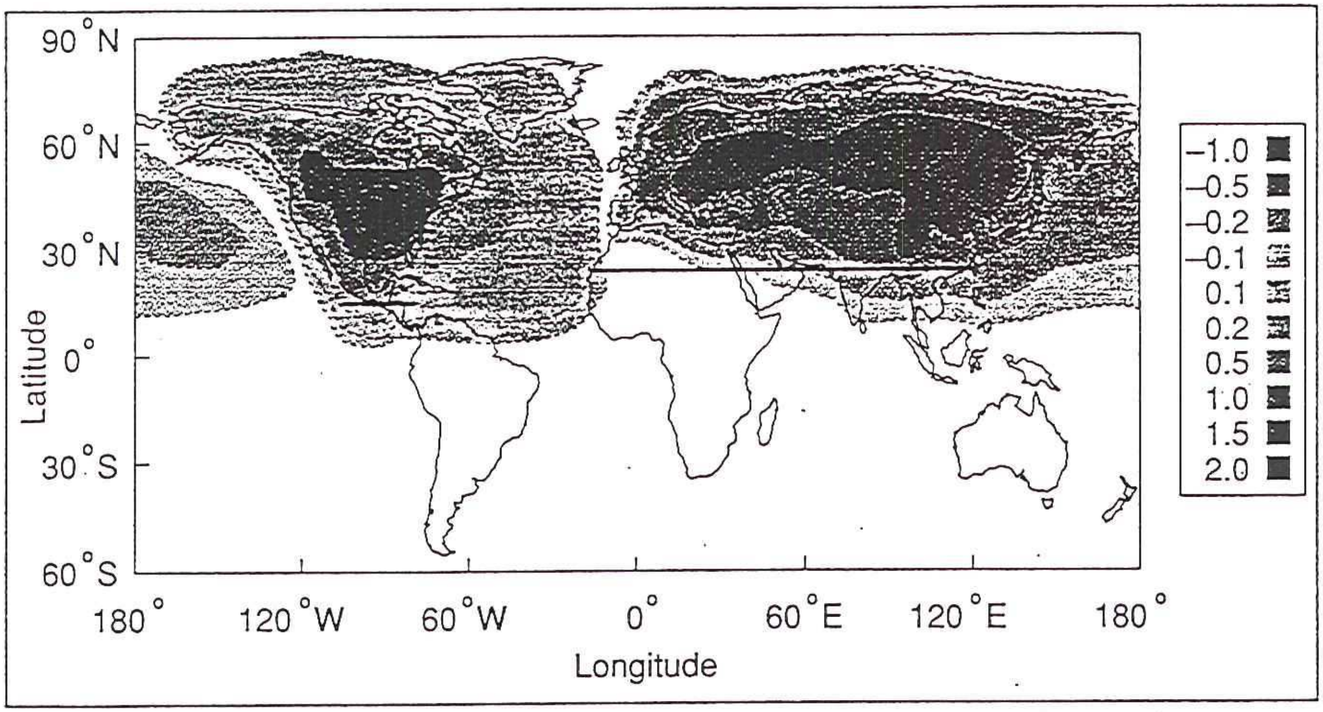
	1996	% change 1990–96
North America	1.75	+8.2
Latin America	0.33	+13.2
EU 15	0.96	+0.8
CIS, C, E Europe	0.90	−31.0
Middle East	0.25	+41.0
Africa	0.22	+19.0
Asia/Pacific	2.00	+31.0
Total OECD	3.27	+7.8
Developing countries	2.34	+32.0
World	6.51	+6.4

Source: World Energy Council

Nature Nov 20, 1997

CLIMATE CHANGE

Possibly Vast Greenhouse Gas Sponge Ignites Controversy



Disappearing act. Contours show how predicted CO_2 levels (in parts per million) would change if there were no terrestrial uptake in North America. Measured levels decline, rather than increase, from west to east North America, however, implying a large carbon sink.

U.S. Oil Still Pours From a Mideast Barrel

By NEELA BANERJEE

Even as talk of war with Iraq and the continuing fallout from Sept. 11 stoke concerns about American dependence on Persian Gulf oil, Western oil companies are showing no intentions of veering away from the Middle East, industry executives say.

The Bush administration has made broadening the sources of America's oil supplies a touchstone of its energy and foreign policies, but officials concede that progress has been slow.

"I believe that the administration's emphasis on increasing and diversifying global energy supplies is having a positive impact on investment decisions — but this impact is difficult to quantify," Spencer Abraham, the energy secretary, said in an interview.

Recently, the administration has encouraged efforts to import more Russian crude oil to the United States and announced plans to open a new consulate in oil-rich Equatorial Guinea. American oil companies say that they welcome such efforts.

But the proportion of United States oil imports flowing from the Middle East remains high — about 24 percent, down from levels during the oil crises of the 1970's, but up by a third over the last few years. And oil executives say that they have not markedly changed their plans for where to seek out, produce and purchase oil.

"Diversifying supply is important for any country, and the industry is looking at other things besides the Middle East," said Clarence P. Cazalot Jr., chief executive of the Marathon Oil Corporation, a Houston-based energy company pursuing projects in the Middle East, West Africa and most recently Russia.

"But at the end of the day, oil has to come from where oil is available, and most

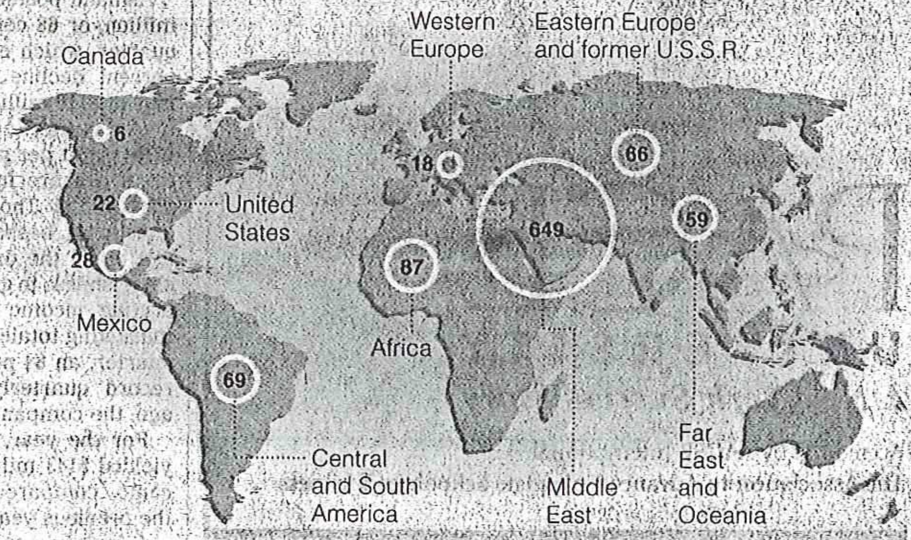
Continued on Page 19

Where the Oil Is

Despite the Bush administration's desire to reduce the nation's dependence on oil from the politically unstable Middle East and the increased efforts by American energy companies to find oil and natural gas closer to home, the region remains at the heart of the business because of its vast reserves.

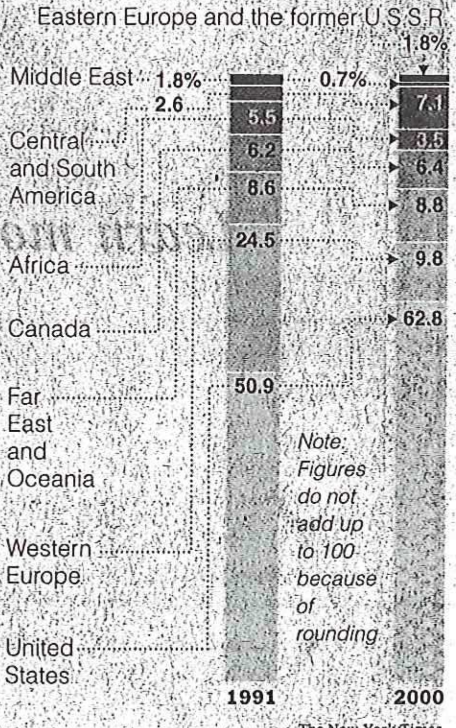
KNOWN OIL RESERVES BY REGION, IN 2000

In billions of barrels



Source: Energy Information Administration

SHARE OF SPENDING ON OIL AND GAS EXPLORATION AND DEVELOPMENT BY UNITED STATES COMPANIES



Note: Figures do not add up to 100 because of rounding.

The New York Times

With White House Approval, E.P.A. Pollution Report Omits Global Warming

By ANDREW C. REVKIN

For the first time in six years, the nnual federal report on air pollution rends has no section on global varming, though President Bush has aid that slowing the growth of emisions linked to warming is a priority or his administration.

The decision to delete the chapter n climate change was made by top fficials at the Environmental Proection Agency with White House approval, White House officials said.

"Some people at pretty high levels n my organization were saying, Take it out,' " said an E.P.A. official utside Washington who helped prepare the report. Others at the agency confirmed his account.

Agency officials say the decision was made for two reasons: the agency has issued two other reports on limate this year, and the annual eport is mainly meant to track pollutants that directly threaten people or ecosystems — substances like lead, carbon monoxide and sulfur dioxide, which causes acid rain.

The report, released early this month, is an overview intended for the public that draws on more detailed E.P.A. data on air pollution trends. Most emissions have been sharply reduced in the last decade, but not carbon dioxide, the heat-trapping gas that most scientists say is the main contributor to global warming. Most carbon dioxide comes from burning fossil fuels.

Industry lobbyists are praising the decision. Coal, oil and car companies say carbon dioxide, which occurs naturally, should not be labeled a pollutant. But environmental groups say the omission reflects the administration's close ties with industry.

"White House censors may have made global warming disappear from this report, but that won't make it disappear as a serious threat to our environment," said Jeremy Symons, an authority on climate policy at the National Wildlife Federation.

Mr. Bush said last year that carbon dioxide appeared to be linked to rising temperatures, and he has since said that voluntary measures should be taken to slow emissions but that the evidence is not yet clear enough to require reductions.

The new report, "Latest Findings on National Air Quality: 2001 Status and Trends," is online, with those from previous years, at: epa.gov/airtrends/reports.html.

Published since the 1970's, the reports have focused on air pollution restricted under the Clean Air Act as directly harming human health or ecosystems. But starting in 1996, the report also included sections on emissions that affect the global atmosphere, including chemicals that damage the ozone layer and carbon dioxide and other greenhouse gases.

The latest report has a section on the ozone-depleting chemicals, which are rapidly being reduced under the 15-year-old Montreal Protocol. But there is no section on climate change.

Global warming is mentioned twice: once in a note in fine print at the bottom of the table of contents, listing agency Web sites with climate data, and once in a paragraph that refers, apparently by mistake, to the omitted section on climate.

"Although the primary focus of this report is on national air pollution," the paragraph says, "global air pollution issues such as destruction of the stratospheric ozone layer and the effect of global warming on the earth's climate are major concerns and are also discussed."

Environmental and conservative groups have accused the administration of sowing confusion on the climate issue.

In late May, the White House approved a climate report that was then submitted by the State Department to the United Nations, though it contained far more dire projections of harm from global warming than Mr. Bush had publicly accepted. The president quickly distanced himself from the report, saying it was "put out by the bureaucracy." New copies of the report have been changed to emphasize scientific uncertainty about the effects of global warming. Some officials at the E.P.A. said the handling of that State Department report heightened concern about climate documents, prompting the changes in the new report.

"There's a complete paranoia about anything on climate, and everything has to be reviewed widely,"

an agency offici
Other officials
changed to avoi
earlier documen
between carbon
ants that fall und
The annual re
lutants "that pos
al threat to hu
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The World

Giant Fields of Dreams

THE magic number is 112 billion. That's how many barrels of oil experts say is oozing through Iraq's geology — the second largest proven reserves of oil on the planet, just behind Saudi Arabia's.

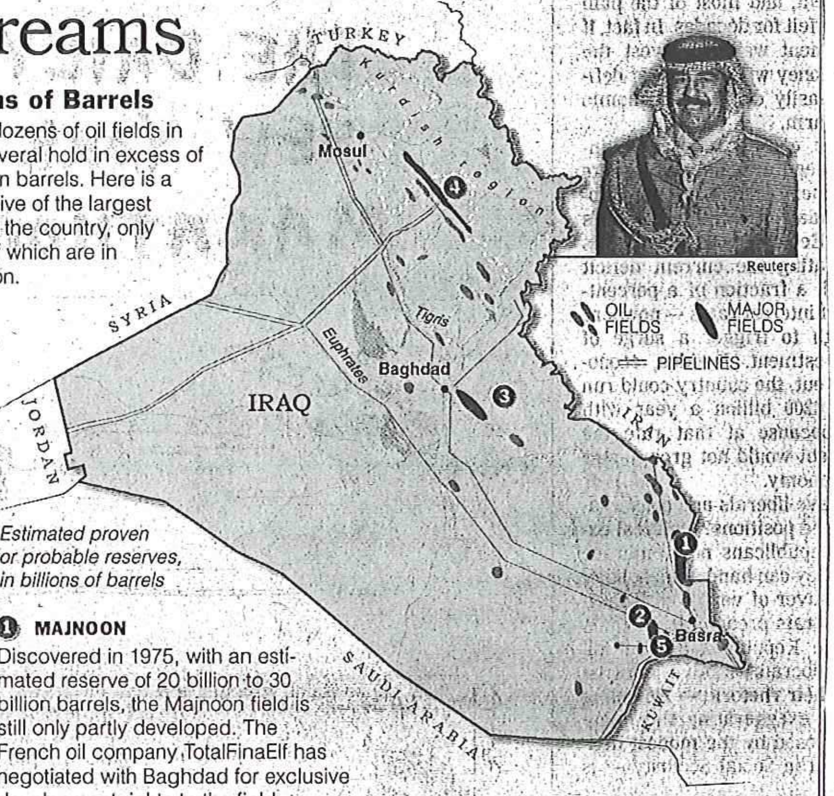
But that's just what is known. Ever since the discovery of oil near Kirkuk in 1927, Iraq has struggled to maximize the commodity's potential for wealth. There are 73 known oil fields in Iraq, but only a third of those are currently producing. Decades of war, sanctions, political instability and lack of resources have left Iraq's oil reserves largely untapped or wholly unexplored. Some analysts speculate that Iraq's reserves may be closer to 200 billion barrels. Others put the number closer to 300 billion.

The wild speculation is at least partly because Iraq's oil exploration thus far has been both shallow (generally no deeper than what geologists call Tertiary or Cretaceous levels), and clustered in the eastern half of the country. Deeper and more western prospecting has yet to be done.

Even the known reserves, however, have yet to be fully developed. There are as many 17 "giant" fields in Iraq — an oil-industry designation indicating reserves in excess of one billion barrels. Throw in a few "super-giants" and a couple dozen "large" fields and the potential is clear, regardless of who controls the country.

Billions of Barrels

Of the dozens of oil fields in Iraq, several hold in excess of 10 billion barrels. Here is a look at five of the largest fields in the country, only some of which are in operation.

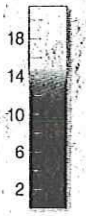


Reuters

Estimated proven or probable reserves, in billions of barrels

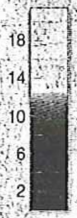
① MAJNOON

Discovered in 1975, with an estimated reserve of 20 billion to 30 billion barrels, the Majnoon field is still only partly developed. The French oil company TotalFinaElf has negotiated with Baghdad for exclusive development rights to the field.



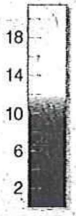
② WEST QURNA

Estimates place reserves here near 15 billion barrels. In March 1997, Russia signed a $3.5 billion, 23-year deal to rehabilitate Iraqi oil fields, including this one — but sanctions, among other obstacles, have so far prevented work from getting started.



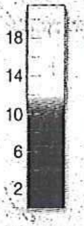
③ EAST BAGHDAD

Oil fields in the central region were among the first to be rehabilitated after the gulf war. The East Baghdad field, found in 1975, has proven reserves of about 11 billion barrels and was brought online in 1989.



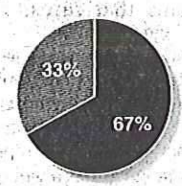
④ KIRKUK

This is the first field discovered in Iraq — 75 years ago this year. It remains one of the country's largest active fields, although a U.N. report last year suggested that Kirkuk was among several fields suffering from severe technical and infrastructure problems.



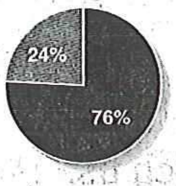
⑤ RUMAILA

The largest active field in the south, Rumaila was one of three fields in the area that, before the invasion of Kuwait in 1990, produced about two-thirds of Iraq's oil output. It is now among several fields that Russia has been eager to develop.



Production status of Iraqi oil fields

- ■ INACTIVE
- ▨ PRODUCING



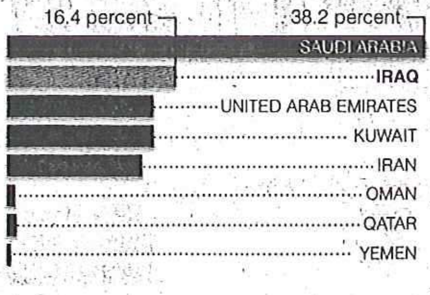
Geologic distribution of Iraqi oil fields

- ▨ TERTIARY (shallower)
- ■ CRETACEOUS
- ☐ not visible: JURASSIC (deeper) **0.1%**

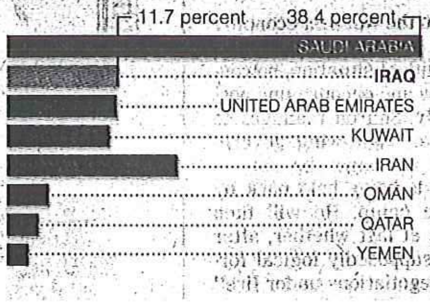
Barely Tapped Potential

Although Iraq has the second largest share of the Middle East's oil reserves, its share of production lags behind that of Iran, which ranks fifth in the Middle East in total reserves.

Share of Proven Oil Reserves, Middle East



Share of Crude Oil Production, Middle East



Sources: United States Department of Energy, Iraq Analysis Brief, October, 2002; Energy Information Administration, International Energy Annual, 2000;

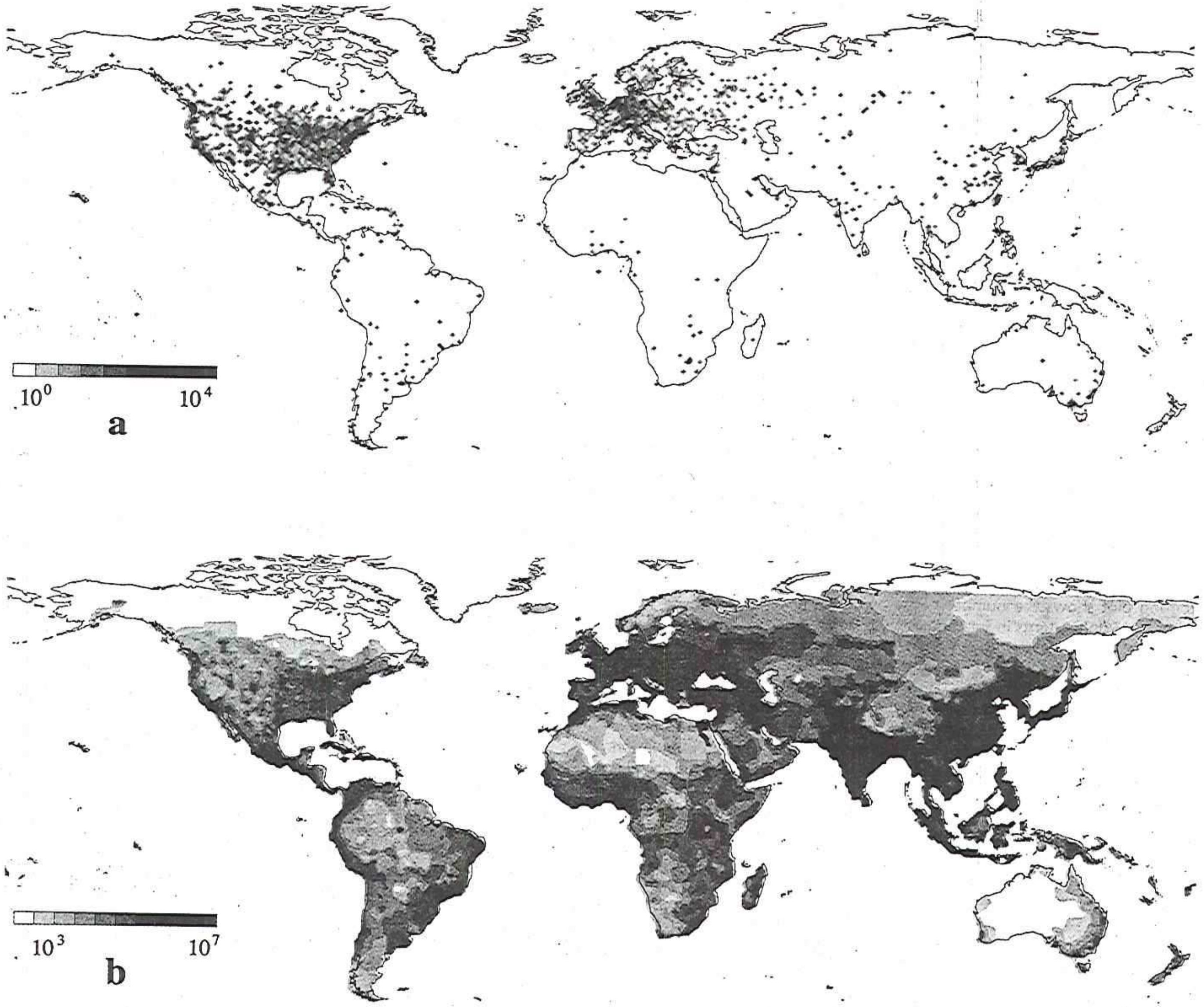


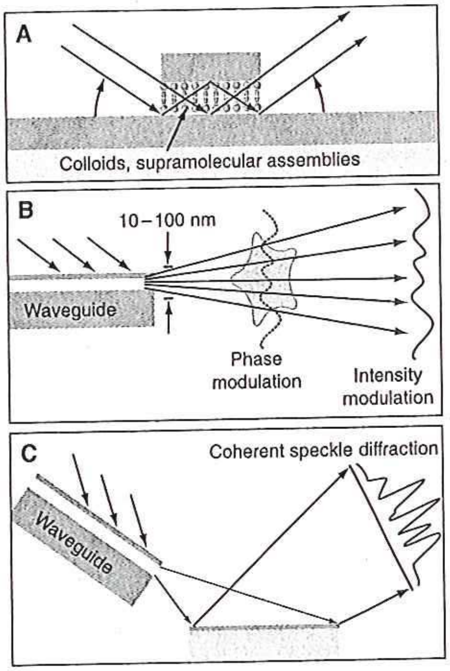
Fig. 1. Distribution of the Internet around the world. (*a*) Worldwide router density map obtained by using the NETGEO tool (www.caida.org/tools/utilities/netgeo) to identify the geographical location of 228,265 routers mapped out by the extensive router level mapping effort of Govindan and Tangmunarunkit.** (*b*) Population density map based on the Columbia University's Center for International Earth Science Information Network's population data (http://sedac.ciesin.org/plue/gpw). Both maps are shown with a box resolution of 1°×1°. The bar next to each map gives the range of values encoded by the color code, indicating that the highest population density within this resolution is of the order 10^7 people/box, while the highest router density is of the order of 10^4 routers/box. Note that while in economically developed nations there are visibly strong correlations between population and router density, in the rest of the world Internet access is sparse, limited to urban areas characterized by population density peaks.

The Measure of the Twentieth Century

Item	Increase Factor, 1890s–1990s
World population	4.0
Urban proportion of world population	3.0
Total world urban population	13.0
World economy	14.0
Industrial output	40.0
Energy use	16.0
Coal production	7.0
Air pollution	5.0*
Carbon dioxide emissions	17.0
Sulfur dioxide emissions	13.0
Lead emissions to the atmosphere	8.0*
Water use	9.0
Marine fish catch	35.0
Cattle population	4.0
Pig population	9.0
Horse population	1.1
Blue whale population	0.0025
Fin whale population	0.03
Bird and mammal species	0.99
Irrigated area	5.0
Forest area	0.8
Cropland	2.0

Source: McNeill.

* Approximate numbers



Waveguide applications. (**A**) Diffraction or spectroscopy of matter incorporated in the waveguide enhances the signal-to-noise ratio through resonance effects. (**B**) Waveguides can also serve as a point source of coherent x-rays. The intrinsic divergence can be used for coherent imaging or photon correlation spectroscopy in a projection setup, in which the information of a nanometer-sized object near the fiber tip is carried to a detector positioned in the far field. (**C**) In contrast to x-ray fiber optics, the beam is coherent; that is, the waveguide acts as a filter for the coherent fraction of the incoming beam, making it useful for photon correlation spectroscopy or coherent scattering.

nances can be excited in two-dimensional (2D) channel structures and clarify the corresponding coupling mechanism.

Many technological improvements will be required before their device can be used as an efficient x-ray point source. However, the reported ~2 × 10^4 photons per second out of a 33 nm by 68 nm opening is already impressive, representing a 70-fold improvement (gain) over a hypothetical pair of slits of the same dimensions under identical instrumental settings.

Given the rapid gain increases in planar waveguides in recent years, similar improvements in 2D waveguides through optimization of the fabrication process are likely. Relative to other focusing techniques, the 2D x-ray waveguide reported by Pfeiffer *et al.* offers unique opportunities for creating coherent hard x-ray beams with spot sizes below 100 nm.

Such beams could probe the structure and the dynamics of individual colloids, nanocrystals, supramolecular assemblies, or organelles in the cell. While structural information can be deduced from imaging or diffraction of the nanobeam, photon correlation spectroscopy may be used to study dynamics, even in the same experimental setup. In the latter case, the waveguide would replace the pinhole currently used in x-ray photon correlation experiments.

As an important step toward these goals, Pfeiffer *et al.* have performed an impressive demonstration of the basic resonance effect, which occurs when one shines a parallel synchrotron beam onto a suitably designed nanostructure. Almost any nanostructure can be analyzed by a diffraction experiment—but not every nanostructure can change the propagation of the beam.

Pfeiffer *et al.* have shown that the interaction of the beam with carefully designed interfaces goes beyond the well-known examples of other beam-shaping devices such as Fresnel zone plates, compound refraction lenses, and planar x-ray multilayers. Their work suggests that the combination of lithographic nanostructures and x-rays may have more surprises in store.

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PERSPECTIVES: PALEOCLIMATE

Earth's Long-Term Memory

Hugo Beltrami

For climate predictions from general circulation models to be interpreted with confidence, a robust record of past climatic changes is required. Without such a record, natural variability of the climate system cannot be separated from the possible changes induced by human activity. Resolving this issue is essential for addressing future climate change.

Two different approaches are widely used to reconstruct Northern Hemisphere climatic change during the last 500 to 1000 years. Both show a warming in the 20th century, but for earlier centuries they observe different patterns of climate change. Do these disagreements reflect only differences in the spatial distribution of sites, or are they due to intrinsic limitations of the methods?

The first method uses large data sets of various temperature proxies, such as tree rings and oxygen isotopes in ice cores, to construct a model of past temperature change (*1*). The second relies on geothermal data from boreholes worldwide to model ground temperature changes and the energy balance at Earth's continental surface (*2*–*4*).

Comparison of these multiproxy and geothermal paleoclimatic models is difficult because of differences in the spatial distribution of data. But preliminary comparison (*5*) yields some important differences. In particular, they disagree over the existence of a cold period between 1500 and 1800 A.D. Such a cold spell is documented in all geothermal models but does not appear as a strong signal in the multiproxy reconstructions (*1*).

To understand these discrepancies, we must first understand how surface temperatures are reconstructed in the borehole method and why direct comparison with multiproxy data is not possible.

If we assume that Earth's upper crust is in thermal equilibrium, then the temperature distribution in the upper few kilometers will be determined by the long-term (>1000 years) surface temperature and the internal heat flow (considered constant for time scales less than 10^6 years). Under the conditions of constant surface temperature and internal heat flow and homogeneous thermal properties of the underground rocks, the temperature increases linearly with depth. In most cases, the subsurface is not homogeneous, but thermal properties can be measured in rock samples and standard corrections applied.

The situation changes if Earth's surface warms (or cools). In this case, a quantity of heat will be gained (or lost) by the ground. These changes in the energy balance at the surface will propagate and be recorded underground as perturbations to the equilibrium thermal regime.

Typically, perturbations penetrate about 20 m in a year, 150 m in 100 years, and 500 m in a millennium, depending on the thermal properties of the subsurface rocks. Hence, recent energy balance changes at the surface remain recorded in the shallow subsurface. Analysis of these underground anomalies provides the basis of the borehole method. The temperature anomalies observed in the Northern Hemisphere (see the figure) show that the spatial variability of the surface energy balance is large.

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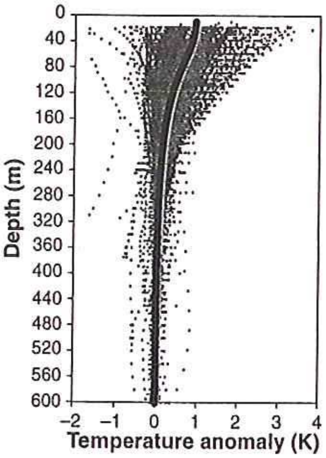
The ground temperature integrates the effects of energy exchange at the air-ground interface, continuously recording the energy balance at the surface. However, other surface factors—such as changes in vegetation cover, underground hydrology, topography variations, lateral heat conduction, and systematic variations of thermal conductivity of the subsurface rocks—can affect the underground thermal regime independently of climate. In fact, geothermal data have been used to determine the time of deforestation in areas of Canada (*6*). Therefore, borehole data must be screened carefully before they are analyzed for climate signatures.

Over the last decade, several groups have reconstructed ground surface temperature histories (GSTHs) from borehole temperatures (*7*). The energy balance at the surface of all the continents (except Antarctica) was estimated, allowing the total heat absorbed by Earth in the last 50 years to be calculated (*4*). Coupled with earlier work (*8*), this information clearly shows that all components of the climate system gained energy during this period, demonstrating the global nature of the present warming of our planet.

To assess the significance of past climatic changes inferred from geothermal data, we must explore the main strengths and limitations of the borehole method. Borehole temperature profiles are not a proxy for surface temperature, but rather a direct measure of the past temperature and energy balance at Earth's continental surface. The underground signal is, however, attenuated considerably through heat diffusion. This signal degradation imposes a physical limit on the information that can be retrieved from subsurface temperature anomalies. No mathematical trickery can overcome these limitations.



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*).

Data noise further decreases the resolution. As a result, the resolution of borehole data decreases with time. A climatic event affecting the ground surface can be resolved only if it persisted for ~60% of the time since its occurrence (*9*). An event that occurred 1000 years ago would therefore be detected as a single event only if it persisted for at least 600 years.

Because the borehole method uses simultaneous inversion (*10, 11*) to obtain site-, regional-, and large-scale averages, the maximum resolution for these ensemble averages is determined by the temperature log with the highest noise level—that is, the log with the lowest potential resolution. The current data set, derived from holes drilled for purposes other than climate reconstruction, represents a trade-off between resolution and spatial representation. Spatially homogeneous dedicated drilling and logging would alleviate this problem.

Because of the loss and variation of resolution through heat diffusion, borehole paleoclimatic reconstructions cannot be related directly to proxy or meteorological records, which contain information at higher and constant resolutions (*12, 13*). How, then, can we compare results from proxy and geothermal climatic reconstructions?

First, to bring the reconstructions to the same resolution, the high-resolution proxy reconstruction must be filtered in the same way as Earth filters surface temperature changes propagating into the ground. This can be accomplished by multiplying the proxy climatic reconstruction time series by the model resolution matrix from the inversion of geothermal data (*12*).

Second, keeping in mind that all paleoclimatic reconstructions are only models of past climatic variations and thus subject to corrections, we must clarify whether the multiproxy reconstruction (*1*) contains sufficient long-term information.

The multiproxy method makes extensive use of tree-ring records, which require substantial preprocessing. A different and arbitrary age-related growth trend removal function is used to filter each tree-ring time series. As a result, trends of more than a few decades may be lost (*5, 14*). Furthermore, filtering takes place at different bandwidths for each tree. All processed dendrochronological time series are subsequently merged to form standardized chronologies. Spectral analysis of processed standardized chronologies is therefore uncertain for periods longer than a few decades.

This problem has recently been overcome by Esper *et al.* (*15, 16*), who reported a new method that preserves long-term trends in tree-ring data. This method must be applied to the tree-ring data used in constructing multiproxy models. The effects of age-related filtering on the long-term results could then be assessed. This reanalysis would not change the conclusions in (*1–4*) regarding the unprecedented character of the rate of change in temperature for the recent warming.

At the same time, regional comparisons of multiproxy and geothermal reconstructions should be carried out wherever allowed by the data. Large-scale averaging of GSTHs may have masked part of the cooling and recovery signal from the so-called Little Ice Age, perhaps because not all boreholes in the analysis have the same depth ranges (the deepest boreholes dominate the long-term GSTH).

For example, in some parts of Canada, evidence from geothermal data for the Little Ice Age is widespread, and in some areas individual GSTHs appear to be similar to the multiproxy reconstruction (*17*), including a cold period qualitatively similar to the Little Ice Age. However, in other parts of Canada, the Little Ice Age is not present in geothermal data (*18*). Examination of such small-scale discrepancies and similarities from proxy and borehole methods should provide insights into how robust the reconstruction methodologies are, and should help to discern the spatial variability of the Little Ice Age.

Clearer insights into past climatic changes should result from integrated analyses in which all models of paleoclimatic reconstruction are interpreted jointly to maximize their strengths and minimize their weaknesses. Interdisciplinary approaches and collaborations across fields are more important than ever in this endeavor.

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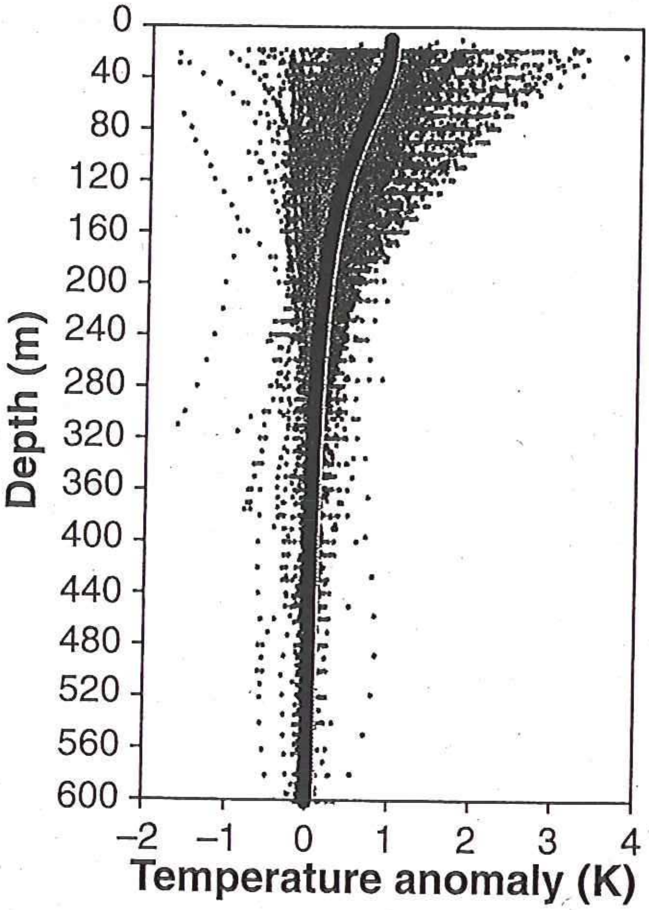
20. Supported by the Natural Sciences and Engineering Research Council of Canada.



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*).

The climate treaty being hammered out this month at The Hague may be doomed to failure; the key, some say, will be keeping the treaty going now and rethinking its controversial goals later

Can the Kyoto Climate Treaty Be Saved From Itself?

SAVING KYOTO

These two articles examine the obstacles to ratification of the Kyoto Protocol.

▶**DOOMED TO FAIL?**

CARBON SINKS

Later this month, representatives from 160 countries will convene at The Hague to work out details of one of the boldest attempts at international diplomacy ever: reining in the gusher of gases threatening to warm the planet. Taking their cue from the successful Montreal Protocol for the control of ozone-destroying emissions, governments crafted the outlines of a "big bang" approach to controlling greenhouse gas emissions at a meeting in Kyoto in 1997. Negotiators established strict targets mandating how much industrialized countries would have to reduce their gas emissions by 2008–12. But they left vague the rules of exactly how countries could achieve these reductions—for instance, how much they could rely on emissions trading or carbon "sinks" (see p. 922). Those details are now on the table at the Hague, and it's the details, some say, that could make or break the protocol.

But even before the meeting, there are murmurings that the negotiations are bound to fail. The United States simply won't ratify any treaty that requires such wrenching reductions, numerous observers say. "I don't know anyone who believes the U.S. is going to ratify this agreement" as it stands now, says economist Henry Jacoby of the Massachusetts Institute of Technology (MIT). Others are less pessimistic, but nobody is truly optimistic. "As it is currently configured, U.S. ratification would be really tough," says economist James Edmonds of the Washington, D.C., office of the Pacific Northwest National Laboratory. And if the United States bails out, the protocol is, if not dead, in very deep trouble. "You don't absolutely have to have the United States," explains Jacoby. "But without the U.S., all of Europe, Japan, and Russia are needed" to meet the requirement that countries responsible for 55% of greenhouse emissions must ratify the treaty to put it in force. Already, policy wonks on the fringes of the negotiations are scrambling for alternatives. Some think that by tweaking the rules, the negotiators at The Hague can sweeten the deal enough so the United States could eventually sign on. But if it is too sweet, other countries may balk. The United States, for example, would like to buy its way out of many of its obligations through deals reducing emissions beyond its borders.

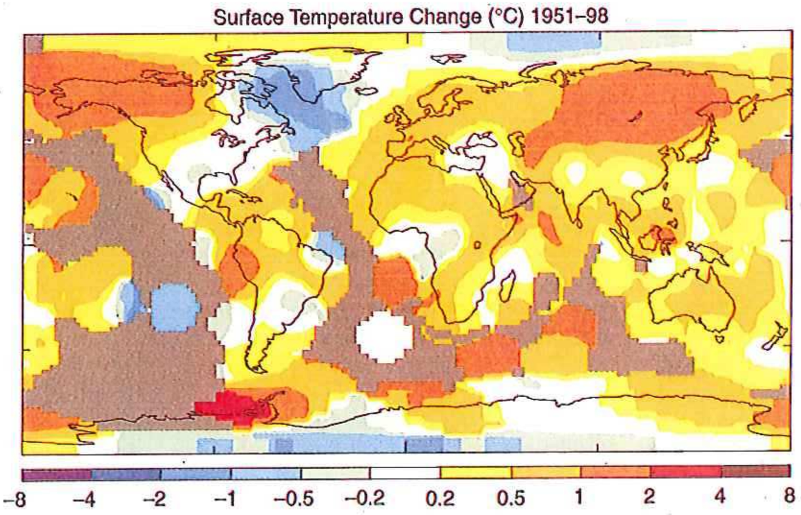
Other analysts say that, eventually, the targets themselves will have to be delayed. Still others are planning how to reduce emissions in a post-Kyoto world if the U.S. bails out completely. None of these options would be popular with many European developing nations, who expect the United States to shoulder emissions cutting at home.

The dim prospects for ratification center on how disruptive and how expensive it would be for countries, particularly the United States, to achieve their target reductions. The protocol calls for an average 5% reduction of emissions below their 1990 level. For the United States, the world's biggest emitter, it mandates a 7% reduction below 1990 levels. What with the robust economic expansion of the past decade, the required U.S. reduction amounts to "a 30% reduction beneath business as usual," notes climate researcher Tom Wigley of the National Center for Atmospheric Research in Boulder, Colorado (see graph on facing page). "Can you imagine the United States in the next 10 years doing that?"

Eileen Claussen can't. She is president of the Pew Center on Global Climate Change in Arlington, Virginia, an organization dedicated to reducing greenhouse emissions. Even so, she says, "I think it's going to become clear to a lot of countries—not just the U.S.—that they're not going to meet their targets. It's already clear the U.S. won't meet its target." Indeed, a Pew Center study of five European countries suggests that only the United Kingdom is on track to meet its Kyoto target, and Germany is perhaps close. Not coincidentally, it's the United Kingdom that vehemently opposes U.S. efforts to buy its way out of substantial emission reductions in its domestic energy sector.

Costs to the United States are "highly uncertain," says economist John Weyant of Stanford University. Given the range of assumptions about Kyoto and the economy, says Weyant, "model projections range from relatively low cost—a couple of tenths of a percent of U.S. gross domestic product [per year]—up to 3% to 4%." For instance, if countries bring online new energy-efficient technologies—everything from light bulbs to hydrogen fuel cells for cars—costs would drop significantly. But major technology changes are unlikely before 2012, Weyant maintains.

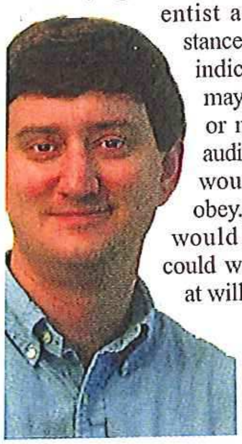
For that reason, U.S. negotiators want to adjust the basic rules, often called the "framework" for the Kyoto Protocol, to allow for maximum flexi-



No return. Even if the goals of the Kyoto Protocol are reached, the recent half-degree warming widely attributed to rising levels of greenhouse gases won't go away for millennia.

SOURCE: GISS

can scan for a watermark, detect the watermark, and make a decision based upon whether the watermark is there," says Scott Craver, a graduate student and computer scientist at Princeton. For instance, the watermark might indicate that an audio file may be copied only once, or not at all—orders that audio players and recorders would be constructed to obey. But such instructions would be moot if hackers could wash off the watermark at will.



Skeptic. Ed Felten says audio watermarks will fail.

SDMI's quest for a secure digital watermark went public in September, when the consortium posted four proposed watermarking schemes and two supplementary technologies on one of its Web sites (www.hacksdmi.org). An accompanying letter offered $10,000 to anyone who could hack any of the security schemes within 3 weeks. "Attack the proposed technologies," read the letter. "Crack them."

Many computer-security experts flatly refused. Don Marti, the technology editor of *Linux Journal*, arguing that SDMI's scheme is a unilateral attempt by the music industry to recast intellectual property rights in its favor, called for a boycott of the HackSDMI effort. "I wanted to call people's attention to the legal rights SDMI is planning to take away," Marti says. Others dismissed the competition as a waste of time. "Challenges and contests are stupid ways of assessing security," says Bruce Schneier, chief technology officer of Counterpane Internet Security in San Jose, California. "If I challenge people to break into my house and it's not robbed in a week, can I conclude that my house is secure? It's bizarre." Craver agrees: "A 3-week challenge could not be taken seriously in the cryptographic community." Nevertheless, Felten, Craver, and others ignored the boycott and attacked the watermarks.

Last week, Felten and Craver's team declared that it had defeated all four watermarking schemes. "Basically, for each of the technologies, we figured out where in the signal each watermark was put and then washed it out," Felten says. "For instance, if it's all stored in a narrow frequency band, you can add a bit of noise in that frequency band." Felten claims that removing the watermarks didn't damage the quality of the music. The SDMI consortium agreed that Felten's sample had no watermark and sounded just fine, at least in a preliminary inspection.

The result proves that "watermarking technology is not mature enough to do what SDMI wants it to do," Felten says. But SDMI isn't convinced. "The word we received was that all 153 attacks have failed to meet the criteria," says David Leibowitz, chair of San Diego–based Verance, which provided one of the four watermarking schemes. SDMI officials say the Princeton team did not submit technical information showing that it had devised a general strategy for defeating watermarks. As Leonardo Chiariglione, SDMI's executive director, explains, "If every bit of new music is a new challenge, if repeatability is not guaranteed, it is not considered a successful attack."

Some experts, though, see Felten's attack as a confirmation that copy-protection schemes will never deter any but the most inept would-be pirate. "Digital bits can be copied; it's the natural way, and any procedure that tries to go against the tide will fail," Schneier says. "Watermarks can't possibly work. Copy protection can't possibly work. Get over it. Accept the inevitable, and figure out how to make money anyway."

–CHARLES SEIFE

INDIA

New Guidelines Promise Stronger Bioethics

NEW DELHI—The Indian government has issued new guidelines for conducting medical research on humans that would raise standards and tighten oversight at most institutions. The voluntary guidelines, released on 18 October, are also expected to bolster international collaborations by putting Indian practices on a par with standards in the West.

Although the guidelines will mean more paperwork for an already clogged bureaucracy, most scientists say that they are an important step toward ensuring ethical research. "It is expected that all institutions that carry out any form of biomedical research involving human beings should follow these guidelines," says Nirmal Kumar Ganguly, director-general of the Indian Council of Medical Research (ICMR) in New Delhi.

Four years in the making, the new guidelines would create a network of institutional review boards. That in itself would be a major change: An ICMR survey last year of 30 leading research institutions found that most had no ethical committees overseeing experiments involving humans. The few committees that did exist were generally moribund, meeting rarely and having little influence on major research decisions.

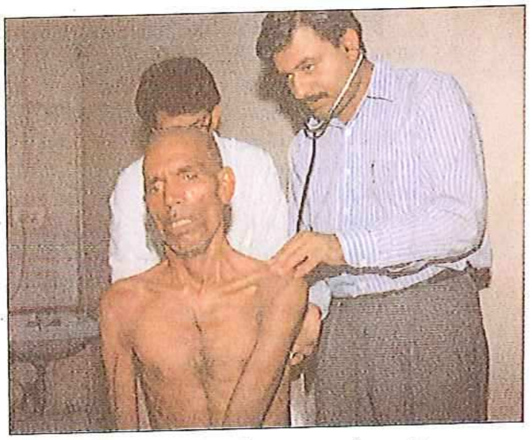
The new guidelines, titled "Ethical Guidelines for Biomedical Research on Human Subjects," stipulate that each research proposal that involves human testing will be vetted by an institutional ethics committee. Its five to seven members must include a legal expert, a social scientist, a philosopher, and a community representative in addition to researchers. All committee decisions will be made at a "formal meeting" and not "through the circulation of a proposal." Once cleared, the protocols would receive no further ethical review.

In addition to enshrining the principles of informed consent and confidentiality, the guidelines specify the nonexploitation of vulnerable groups such as the poor and mentally challenged people. It also says that anyone in a trial who has an adverse reaction should receive the "best possible nationally available care."

The guidelines were unveiled at a meeting here of the Indo–U.S. Biomedical Research Policy Forum, which seeks to resolve obstacles to collaborative biomedical research between the two countries. Gerald Keusch, director of the Fogarty International Center of the U.S. National Institutes of Health, who attended the meeting, called the guidelines "comprehensive." He said they "have the same philosophic context" as those that federally funded researchers and their U.S. institutions must follow.

Absent binding legislation and additional resources, the success of the voluntary guidelines will depend on the response of the scientific community. "There is no way the ICMR can be the policing agency," says Vasantha Muthuswamy, chief of basic biomedical research at ICMR and secretary of the Central Ethics Committee on Human Research, which formulated the guidelines. And that puts the burden on those who fund the research, as well as those who carry it out. "Now that a strong ethical framework has been put in place, it is up to the grant-giving agencies to ensure that funding is not given in instances where ethical violations are noticed," says Prakash Narain Tandon, a neurosurgeon and professor emeritus at the All Indian Institute of Medical Sciences in New Delhi.

–PALLAVA BAGLA



Standard of care. Indian doctors examine a tuberculosis patient being recruited for a drug trial.

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A Well-Intentioned Cleanup Gets Mixed Reviews

Climate researcher James Hansen just wanted to help. By publishing an alternative, and decidedly upbeat, scenario for how greenhouse warming might play out in the next half-century, the director of NASA's Goddard Institute for Space Studies (GISS) in New York City hoped to open new prospects for attacking the problem. Instead, he got a lot of grief. "Some very thoughtful people didn't understand what we were saying," he said at a recent workshop on his alternative scenario. "The paper has been misconstrued by both ends of the spectrum."

Dirty heater. Soot can warm climate

Rather than abandoning his position that rising levels of carbon dioxide from the burning of fossil fuels pose a serious threat to society, as some observers supposed, Hansen merely was trying to emphasize that there is more to the greenhouse problem than carbon dioxide. Specifically, controlling many of the components of what's popularly regarded as "pollution"—dirty hazes and throat-searing smog—would also help, perhaps through the use of more renewable energy and inherently clean fuels like natural gas.

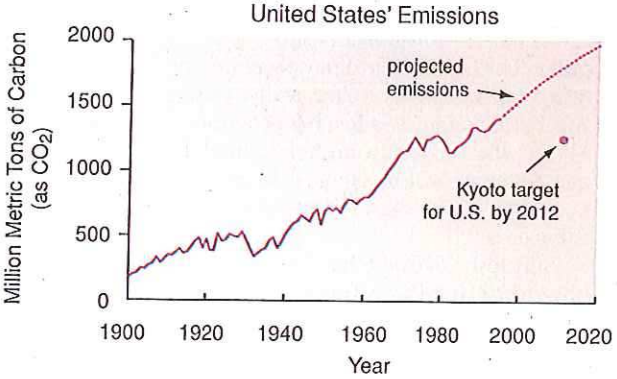
Hansen's proposed scenario, published in the 29 August issue of the *Proceedings of the National Academy of Sciences*, rests on the observation that the warming effect of carbon dioxide so far seems to have been largely counterbalanced by the cooling effect of pollutant hazes, which reflect solar energy back to space. That cancellation, Hansen and four colleagues from GISS write, points up that there are additional targets for reducing warming in the next 50 years, including such pollutant greenhouse gases as methane from rice paddies, chlorofluorocarbons from air conditioners, and the ozone of smog—as well as dark, soot-laden aerosols from such sources as diesel engines and agricultural burning. Holding these pollutants in check over the next 50 years is plausible, they argue—indeed, much of it is already being done, at least in the United States, under the Clean Air Act and the Montreal Protocol. It is also possible to reduce the growth rate of carbon dioxide in the atmosphere so as to hold the warming from that gas to a modest amount, says Hansen, who reiterates: "We're not de-emphasizing carbon dioxide." Although resource economist Henry Jacoby of the Massachusetts Institute of Technology doesn't see much new in Hansen's latest proposal, he does see an upside. "The point is, you have to go after everything." **–R.A.K.**

bility. Emissions trading among nations may enable the most wiggle room. As outlined in the protocol, an industrialized nation that doesn't want to reduce its own emissions could buy a permit from another industrialized nation to emit so many tons of greenhouse gas, presumably at a lower cost. But there's a catch. Trading is already restricted to industrialized countries, and the United Kingdom has floated a proposal that restricts the proportion of a country's reductions—read, the United States—that can be taken this way.

Another means of adding flexibility is the protocol's Clean Development Mechanism. The CDM would allow an industrialized country to join with a developing country, which under the protocol has no obligation to reduce emissions, in an emission-reducing project in that country. The idea is that the developing country would reap the benefits of a nonpolluting energy source and the industrialized country would get credit for the reduced emissions. But again, the devil is in the details. What projects would qualify? A nonemitting nuclear power plant? An ecologically disruptive hydroelectric dam? Some proposals stipulate that only renewable energy and energy-efficiency projects qualify.

Claussen, who played a key role in negotiating the protocol while at the State Department, thinks getting the right rules in place is the first step. Basically, she would like to see minimal restrictions on flexible mechanisms such as CDM and on carbon sinks. Then, "after the framework is in place, people may still say, 'Oh my, we're not going to make it,' and there will be some adjustment of the targets."

Some think Claussen is being overly pessimistic. Daniel Lashof of the Natural Resources Defense Council in Washington, D.C., says, "It looks like the U.S. will get a lot of the flexibility it wants" at The Hague. Even so, the country "should and can get the majority of reductions domestically," he contends. "What will decrease future emissions is requiring firms to invest in emission reduction now."



Environmentalists may not see the necessity of delaying implementation of big emission reductions, but a lot of economists do. "Kyoto is a political compromise designed to get us moving on carbon-emission reductions," says Weyant. But "studies suggest it's not an optimum path" to the unspoken goal of Kyoto: stable greenhouse gas concentrations a century or two from now. Whereas the environmentally inclined insist that the world must tackle the greenhouse with vigor now, economists like Michael Toman and his colleagues at Resources for the Future (RFF) in Washington, D.C., argue that the world can reach its long-term goal much more cheaply by putting off much—but not all—of the needed emission reductions. This "back-loading" of deep cuts in emissions would be cheaper, Toman argues, because it would allow an orderly replacement of long-lived, fuel-burning equipment and the use of technology not yet available, among other advantages.

Economists also have alternatives intended to keep costs down and reassure countries that costs won't skyrocket. William Pizer of RFF, for instance, proposes a "safety valve" approach. The costs of emission permits could float until they hit a predetermined ceiling, so governments would know in advance the worst case, or most expensive, scenario. MIT's Jacoby agrees: "You need some sort of safety valve so governments aren't committing to something they can't meet. That's going to take time." He notes that it took 50 years for the General Agreement on Tariffs and Trade to evolve into the 138-nation World Trade Organization. Kyoto might evolve the same way, he says. "A few countries agree on really narrow things and gradually build up a system over time, in contrast to the 'big bang' approach of Kyoto. That way, it doesn't die."

–RICHARD A. KERR

SAVING KYOTO
▶CARBON SINKS

Soaking Up Carbon in Forests and Fields

The climate treaty left open the rules for using managed forests, rangelands, and croplands to help meet Kyoto targets. How should it be done?

Is it fair for global bookkeepers to let countries subtract carbon sequestered by their farmland and forests from the carbon they spew by burning fossil fuels? If so, how do you measure how many tons of carbon an Iowa cornfield has socked away? Those questions will be high on the agenda as negotiators meet later this month to nail down the details of the Kyoto Protocol (see p. 920). Forests and other land sinks, as they are called, could offset a sizable chunk of the extra CO_2 that humans pump into the atmosphere and protect biodiversity as well. But sinks are controversial, both because of uncertainties about how to measure the carbon they absorb and because some countries view sink proposals—particularly the United States'—as a distraction to avoid cutting fossil fuel emissions.

The Kyoto Protocol includes land sinks because they're a big part of the global carbon equation. Carbon dioxide taken up by plants and soils through photosynthesis balances a whopping 2.3 of the 7.9 petagrams of the carbon belched into the atmosphere annually by human activity. (Conversely, cutting and burning forests adds 1.6 petagrams.) That's why the Kyoto Protocol stipulates that countries will be credited for planting new forests and docked for cutting down existing ones.

Still to be decided, however, is exactly how to define these forests, as well as whether to include other lands managed since 1990 to absorb carbon, for example by sustainably harvesting timber and using no-till methods on farmlands. Carbon sinks are no panacea—forests and fields would absorb less and less carbon as decades pass—but "it could make a heck of a difference" in the short term, says soil scientist Neil Sampson, a consultant in Alexandria, Virginia, who helped write a recent report on sinks from the Intergovernmental Panel on Climate Change (IPCC) (*Science*, 12 May, p. 942). Letting U.S. farmers make money from sequestering carbon could also win much-needed support for the treaty from Midwestern conservatives in the U.S. Senate.

But crediting countries for such sinks would require massive surveys. For forests, it's fairly straightforward: Most industrialized countries already track the growth of their forests for timber-harvesting purposes. They typically use a combination of remote sensing, modeling, and on-the-ground measurements, such as carbon analysis of trees, leaf litter, and soil. Even many environmental groups who have some qualms about sinks are fairly comfortable with forest sink accounting, as long as there are provisions to prevent unintended ecological harm, such as mowing down old-growth forest to create tree plantations. "There are some questions about how good the inventory systems are, but in my view they can be overcome," says Daniel Lashof, a senior scientist with the Natural Resources Defense Council in Washington, D.C.

Carbon crop. Canadian researchers have studied the cost of measuring carbon in farmland managed so as to sop up CO_2.

With farmlands and rangelands, however, monitoring is more uncertain because no system is in place. For example, the National Resource Inventory at the U.S. Department of Agriculture tracks nitrogen content and soil erosion on farmlands but doesn't routinely measure carbon. Measuring the carbon added by, say, no-till practices could be horrendously difficult, says ecologist Mac Post of Oak Ridge National Laboratory (ORNL) in Tennessee. For one, the amount of carbon absorbed would be tiny—overall, an annual change of 50 grams per 7 kilograms of soil—and it would vary with crop type, weather, and even from furrow to ridge within a field.

Improving these numbers by sampling each farmer's field just wouldn't be practical: "You'd probably produce more CO_2 than you gained," says biogeochemist Ben Ellert of Agriculture and Agri-Food Canada (AAF However, a pilot project in Saskatchewan . convinced some experts that a statistical approach can bring down the costs of measuring carbon uptake. The 3-year project, supported by energy utilities interested in buying carbon credits from farmers, combined statistical sampling with modeling on 150 farms. It concluded that carbon absorbed by changes in land use could be measured for a relatively low 10 to 15 cents per hectare, according to Brian McConkey of AAFC. And better technologies are on the way, says ecologist Keith Paustian of Colorado State University, Fort Collins: A group at Los Alamos National Laboratory in New Mexico, for example, has invented a sensor for detecting carbon just by sticking the tool in the soil, eliminating the need to cart samples to a lab.

Even if monitoring sinks is doable, a host of policy questions remain. Protecting a forest in one part of a country, for instance, may lead to logging elsewhere. Another concern is the impermanence of projects: A credited forest might eventually be destroyed by a hurricane, for example. One solution laid out by the IPCC sinks report and now endorsed by many groups is to count the carbon going in and out of *all* of a country's lands, no matter the type, instead of giving credit for specific activities. "[illegible]ing at the whole landscape will bring us closer to what the atmosphere is actually seeing," says biophysicist Darren Goetze, a global change consultant in Ottawa.

Still, the uncertainties over measurement are one reason why some want to hold off on giving credit for sinks until the second phase of the treaty, after 2012. Including sinks also faces fierce opposition from the European Union, which rejects the idea because it would allow countries to avoid reducing their fossil-fuel emissions.

Even some sink proponents see the U.S. position as too greedy. It seeks credit for part of the 310 million metric tons of carbon per year that U.S. forests and fields will absorb between 1990 and 2012—even without any new intervention. That adds up to half of the U.S. target emissions cuts. Most other countries, arguing that only deliberately created sinks should count, won't be willing to accept these credits, says geochemist Gregg Marland of ORNL.

Whether or not countries get credit for their sinks, many scientists look forward to a global effort to monitor the carbon sucked up by the world's green spaces. As Paustian says, "Irrespective of carbon trading, we need to understand the role of the carbon sink" to improve global models and predict how much the world may warm in the future.

–JOCELYN KAISER

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