Green Chemistry Metrics

Factor	Dimension	Comment
PET production (as fibre)	500 000 $t\,y^{-1}$	World-scale plant
Area occupied by PET production	ca. 4 ha	Assume area needed for infrastructure (raw material/energy provision, processing) for chemicals production and sheep-rearing are similar
Average weight of sheep fleece	3.8 kg	Round up to 5 kg
Number of sheep to give weight of wool equivalent to PET fibre	ca. 100 000 000	Assume technical and performance equivalence of PET fibre and wool
Number of sheep sustained by best pasture	ca. 25 per ha	Assume all pasture able to sustain at this level
Area of pasture required	4 000 000 ha	40 000 km^2 (land area equivalent to the size of Holland)
Land-use intensification factor	10^6	To within ±1 order or magnitude

Other factors: Disposal of 15–20 $M\,y^{-1}$ sheep carcasses
Waste produced from meat and wool processing
Impact of climatic, seasonal and disease factors
Hazards associated with sheep shearing

Box 1.1 Land-use intensification from chemicals production.

and CO_2 content of fuels

Fuel	FW	kJ/mol	kJ/g	molCO_2/mol	molCO_2/kg	molCO_2/MJ
Hydrogen	2	-286	-143	0	0	0
Methane	16	-890	-55.6	1	63	1.12
Isooctane	114	-5461	-47.9	8	70	1.46
Benzene	78	-3268	-41.9	6	77	1.84
Methanol	32	-726	-22.7	1	31	1.38
Ethanol	46	-1368	-29.7	2	43	1.46
Carbon	12	-394	-32.8	1	83	2.54
Biodiesel	298	-11962	-40.1	19	64	1.59

- NIST Chemistry webbook: http://webbook.nist.gov/chemistry/

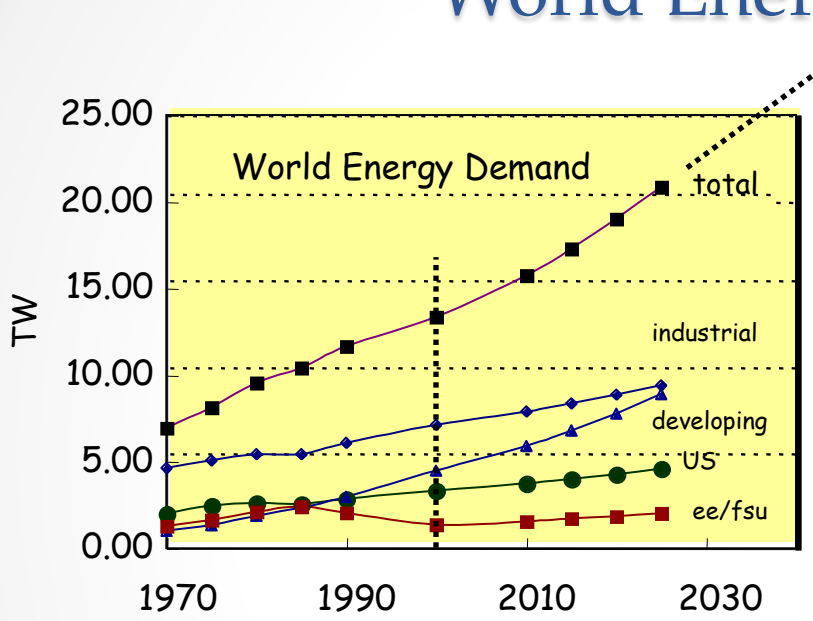
Energy Issues

Lewis, N. S.; Nocera, D. G. *Proc. Natl. Acad. Sci. USA* **2007**, *103*, 15729-15735.

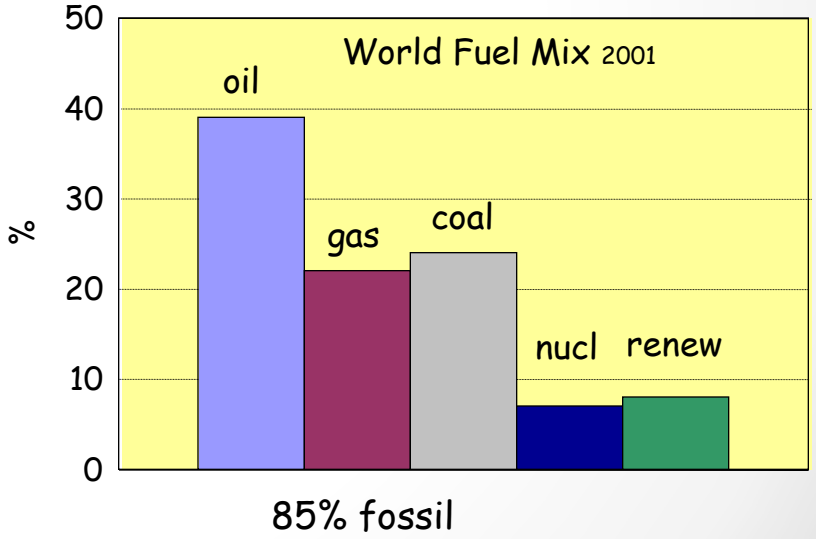
Cho, A. *Science* **2010**, *329*, 786-787

http://mageep.wustl.edu/Program2010/Presentations/Other/Calabrese.pdf
http://en.wikipedia.org/wiki/World_energy_resources_and_consumption

World Energy Demand



energy gap
~ 14 TW by 2050
~ 33 TW by 2100

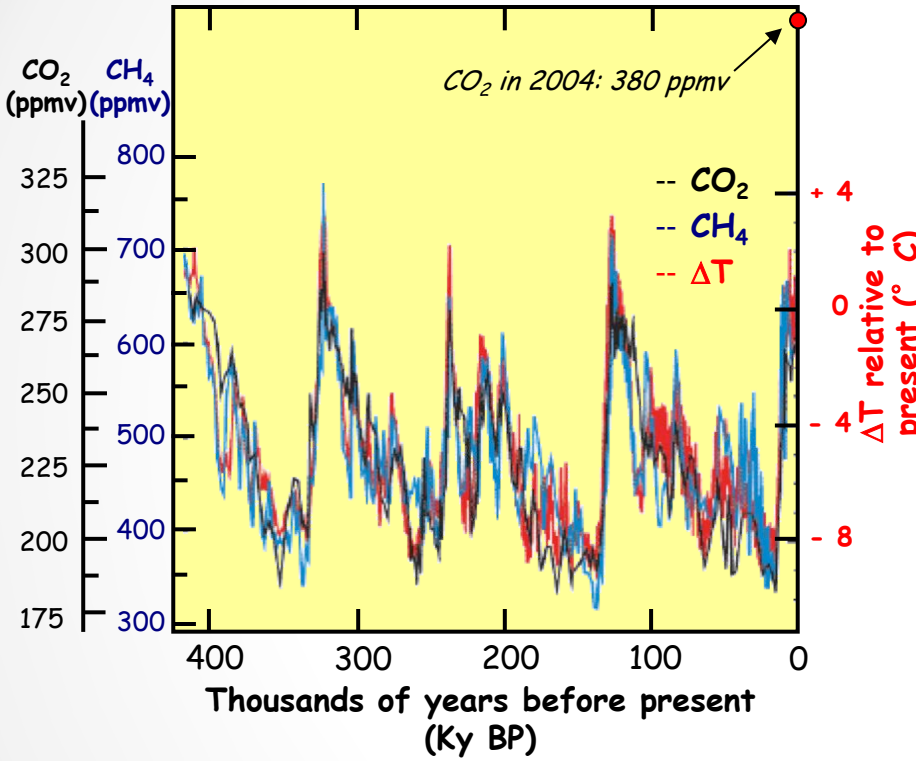


85% fossil

EIA Intl Energy Outlook 2004
http://www.eia.doe.gov/oiaf/ieo/index.html

Hoffert et al Nature 395, 883,1998

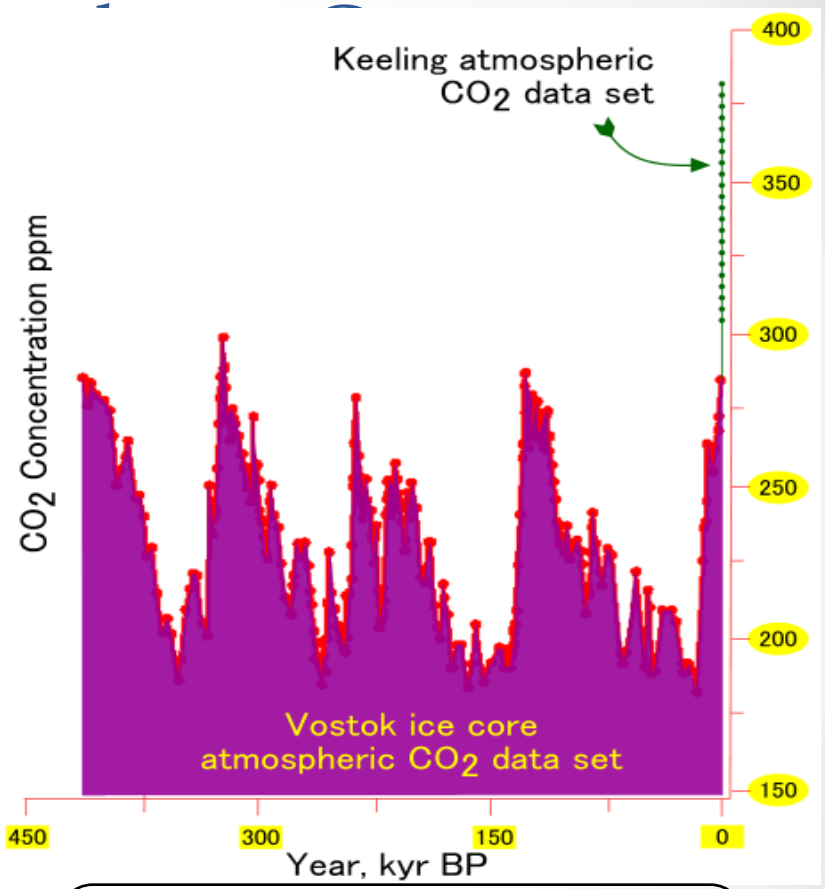
Fossil Fuels and Gre



Climate Change 2001: T he Scientific Basis, Fig 2.22

Intergovernmental Panel on Climate Change, 2001
http://www.ipcc.ch

*N. Oreskes, Science **306**, 1686, 2004*
*D. A. Stainforth et al, Nature **433**, 403, 2005*



Relaxation time

transport of CO_2 or heat to deep ocean: >3000 years

- ~ 14 TW of additional power by 2050
- ~ 33 TW of additional power by 2100
- 2004 capacity: 13 TW

fossil energy

after oil production peaks, switch to gas and coal

capture/store 22 Gtonnes of CO_2/yr (current emissions)

- 12,500 km^3 at atmospheric pressure = volume of Lake Superior
- 600 times CO_2 injected in oil wells/yr to spur production
- 100 times the natural gas drawn in and out of geologic storage/yr to smooth demand
- 20,000 times CO_2 stored/yr in Norway's Sleipner offshore reservior
- no leaks: 1% leak rate nullifies storage in 100 yrs

nuclear energy

14,000 1 GW_e fission reactors - 1 new reactor/day for 38 years

Renewable Sources

Solar

- 1.2×10^5 TW at Earth surface
- 600 TW practical

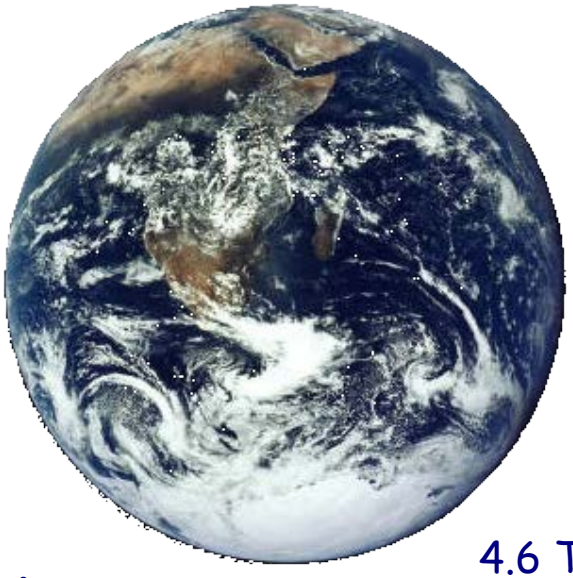
energy gap
~ 14 TW by 2050
~ 33 TW by 2100

Wind

2-4 TW extractable

Biomass

5-7 TW gross
all cultivatable land not used for food



Tide/Ocean Currents

2 TW gross

Hydroelectric

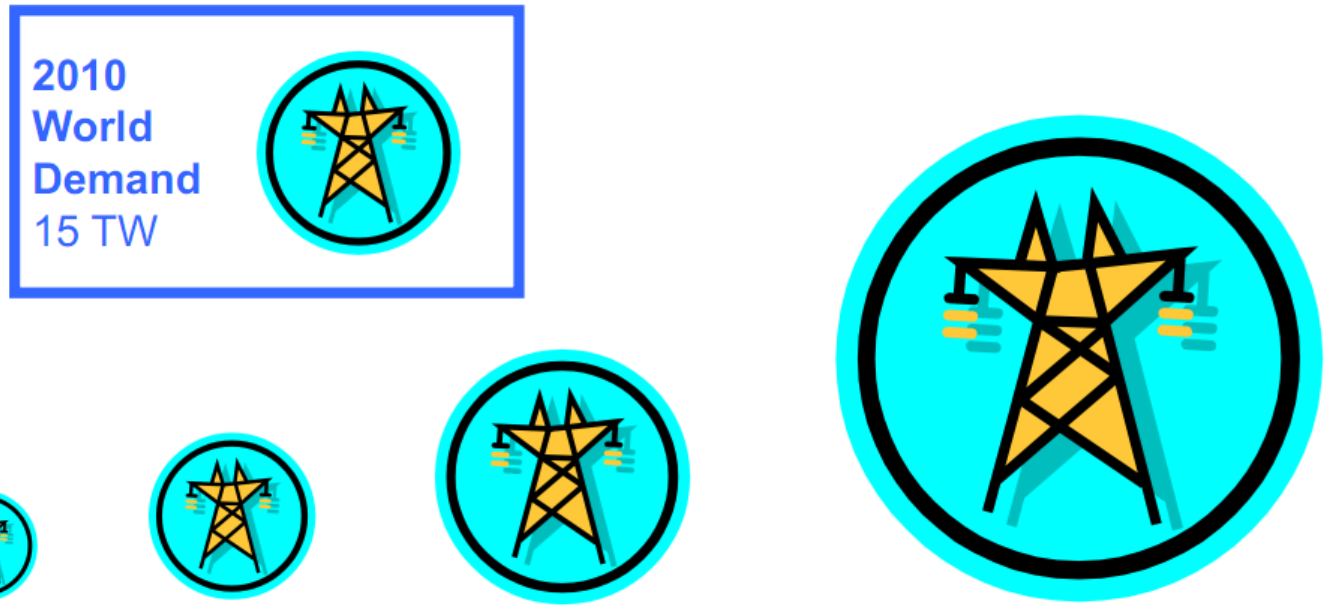
4.6 TW gross
1.6 TW technically feasible
0.9 TW economically feasible
0.6 TW installed capacity

Geothermal

12 TW gross over land
small fraction recoverable

Renewable sources have enough power

Estimated practically available power



Hydro 1.6 TW

Geothermal 3.8 TW

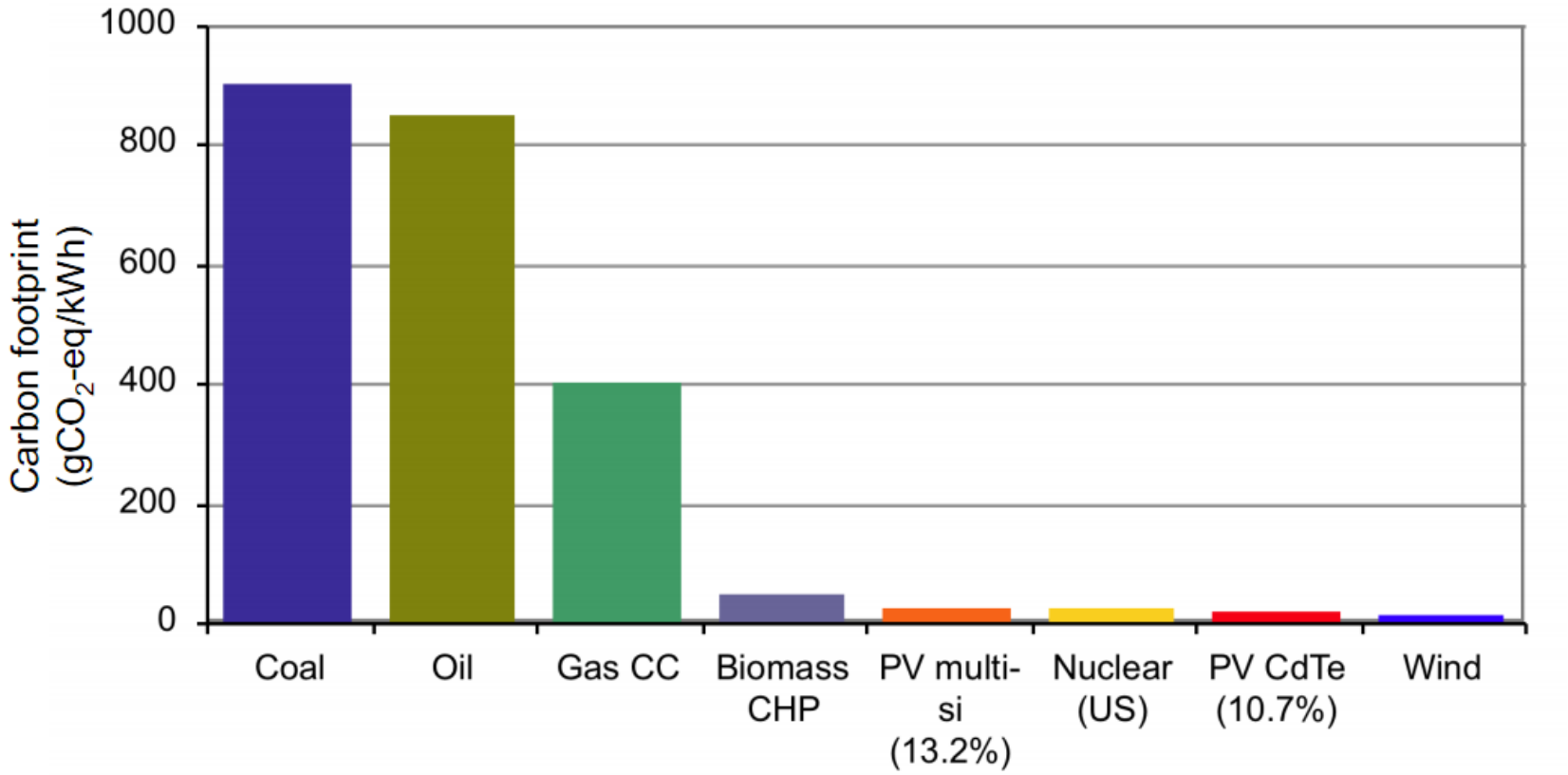
Biomass 9 TW

Wind 20 TW

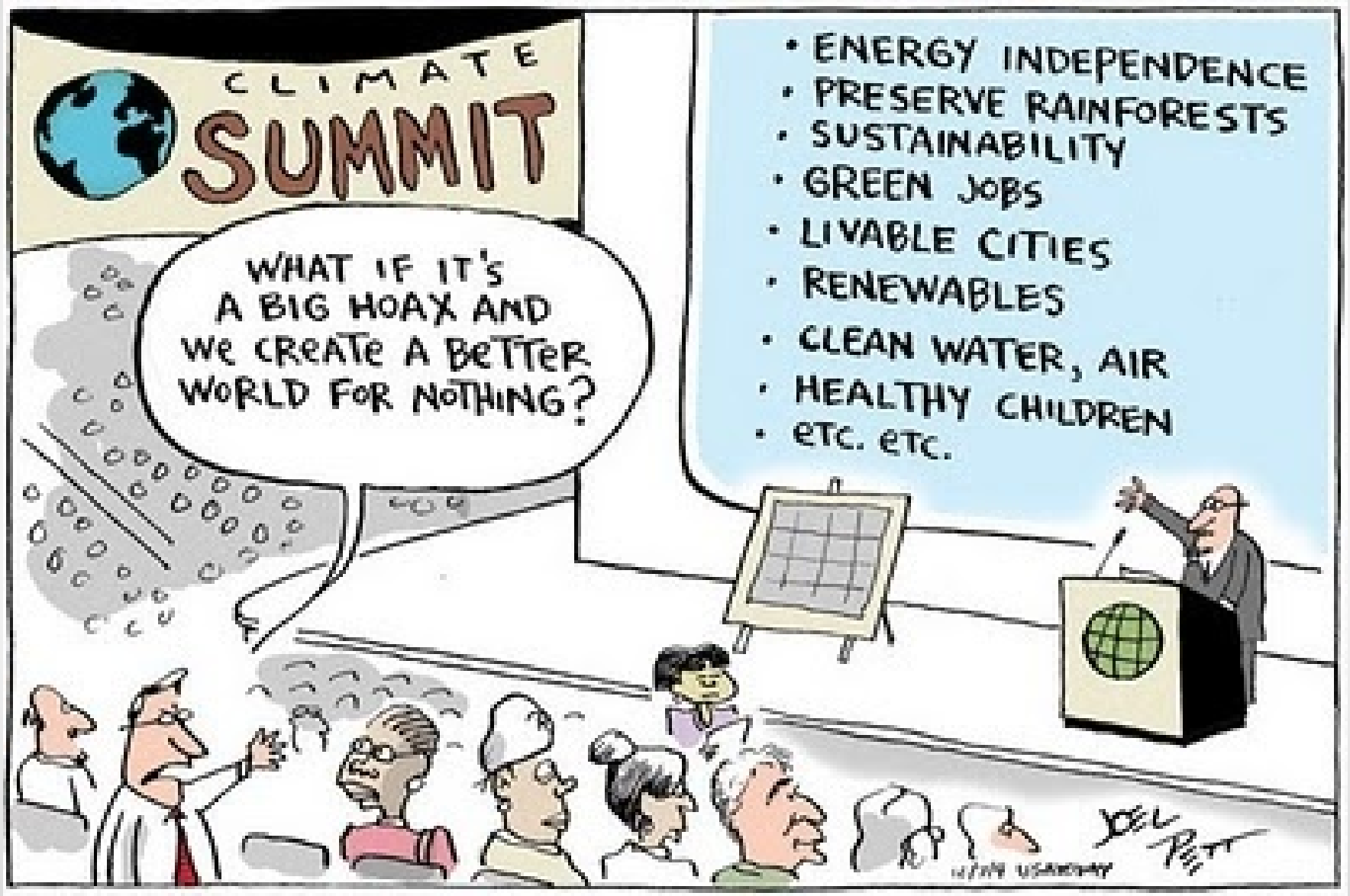
Solar >50 TW

Source: A. Cho, Science 329, 786-787 (2010). IEA estimates for Solar, Biomass and Hydroelectric are 2x-4x these numbers. Lewis & Nocera estimates in *PNAS* Perspective, 2006 are similar to those above except for Solar, which they estimate at 800 TW practical.

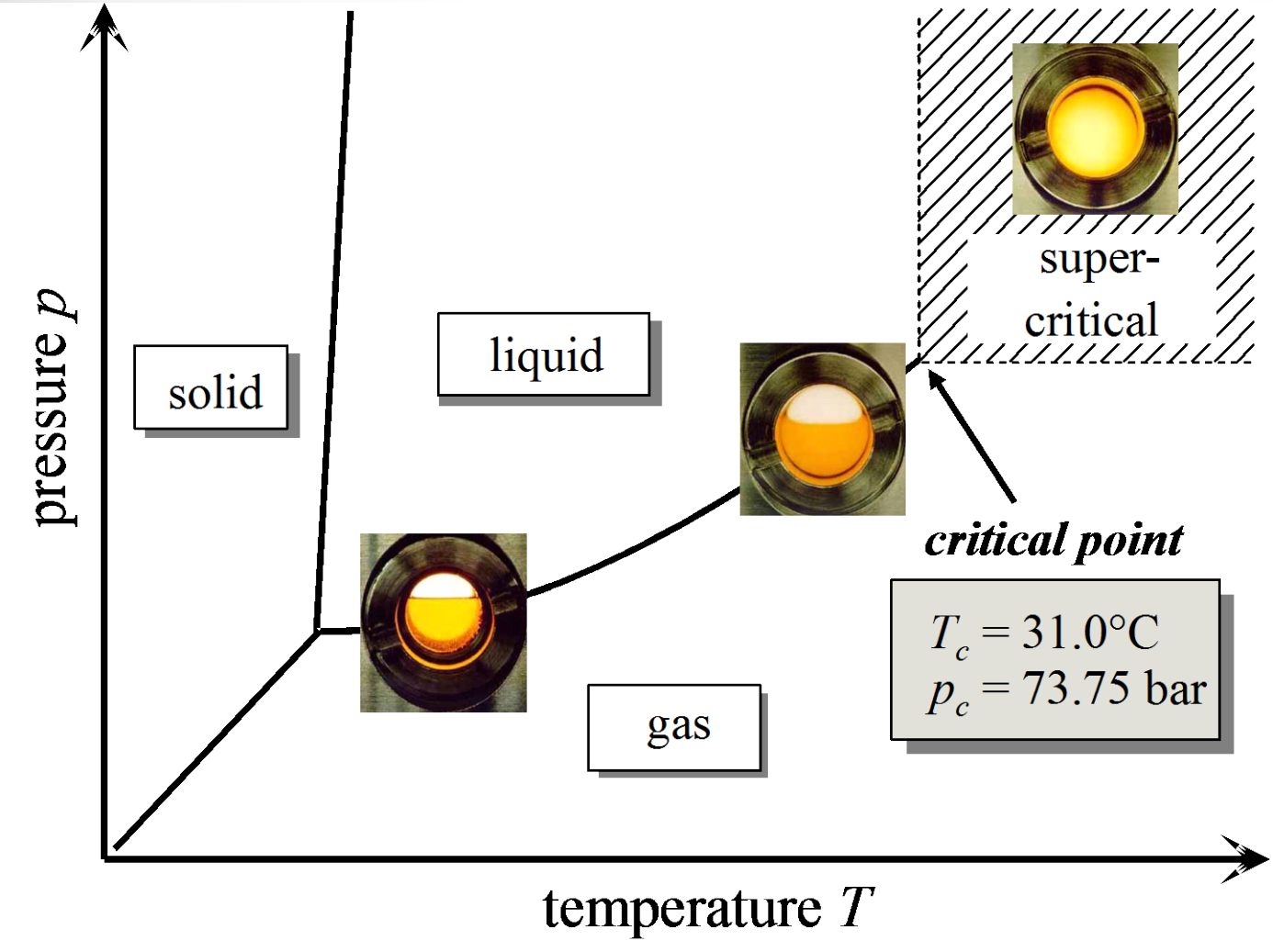
… and CO_2 emission problem …



Sources: *de Wild-Scholten, M., presented at CrystalClear Final Event in Munich on May 26, 2009. **de Wild-Scholten, M., 'Solar as an environmental product: Thin-film modules – production processes and their environmental assessment,' presented at the Thin Film Industry Forum, Berlin, April, 2009. Both PV technologies use insolation of 1700 kWh/m2. All other data from ExternE project, 2003; Kim and Dale, 2005; Fthenakis and Kim, 2006: Fthenakis and Alsema, 2006; Fthenakis and Kim, in press. First Solar


CLIMATE
SUMMIT
WHAT IF IT'S A BIG HOAX AND WE CREATE A BETTER WORLD FOR NOTHING?
• ENERGY INDEPENDENCE
• PRESERVE RAINFORESTS
• SUSTAINABILITY
• GREEN JOBS
• LIVABLE CITIES
• RENEWABLES
• CLEAN WATER, AIR
• HEALTHY CHILDREN
• ETC. ETC.
JOEL PETT

Reaction Conditions



Our typical reaction conditions:

- 35-55 bar CO_2 and 80°C
- Clearly in the subcritical region

Table 3.3

Calculated and Actual Temperatures of the Surfaces of Planets and the Moon

Planet	Distance from Sun, 10^9 m	Calculated Temperature °K	Actual Temperature °K	ΔT
Venus	108	252	730	+478
Earth	150	255	288	+34
Earth's moon	150	270	274	+4
Mars	228	217	218	+1

Source: Adapted from M. Z. Jacobson. *Atmospheric Pollution* (Cambridge, UK: Cambridge University Press, 2002), p. 314.

Table 3.4

Properties of Anthropologic Greenhouse Gases

	CO_2	CH_4	N_2O	Freon-11	Freon-23
Atmospheric concentration	ppmv	ppbv	ppbv	pptv	pptv
Preindustrial (1750–1800)	~280	~700	~270	0	0
Current	370	1745	314	268	14
Current rate of change/year*	1.5	7.0	0.8	−1.4	0.55
(% increase/year)	0.41	0.40	0.25	−0.52	3.92
Atmospheric lifetime (years)	5 to 200†	12	114	45	260

* Rate is calculated over the period 1990–1999.

† No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

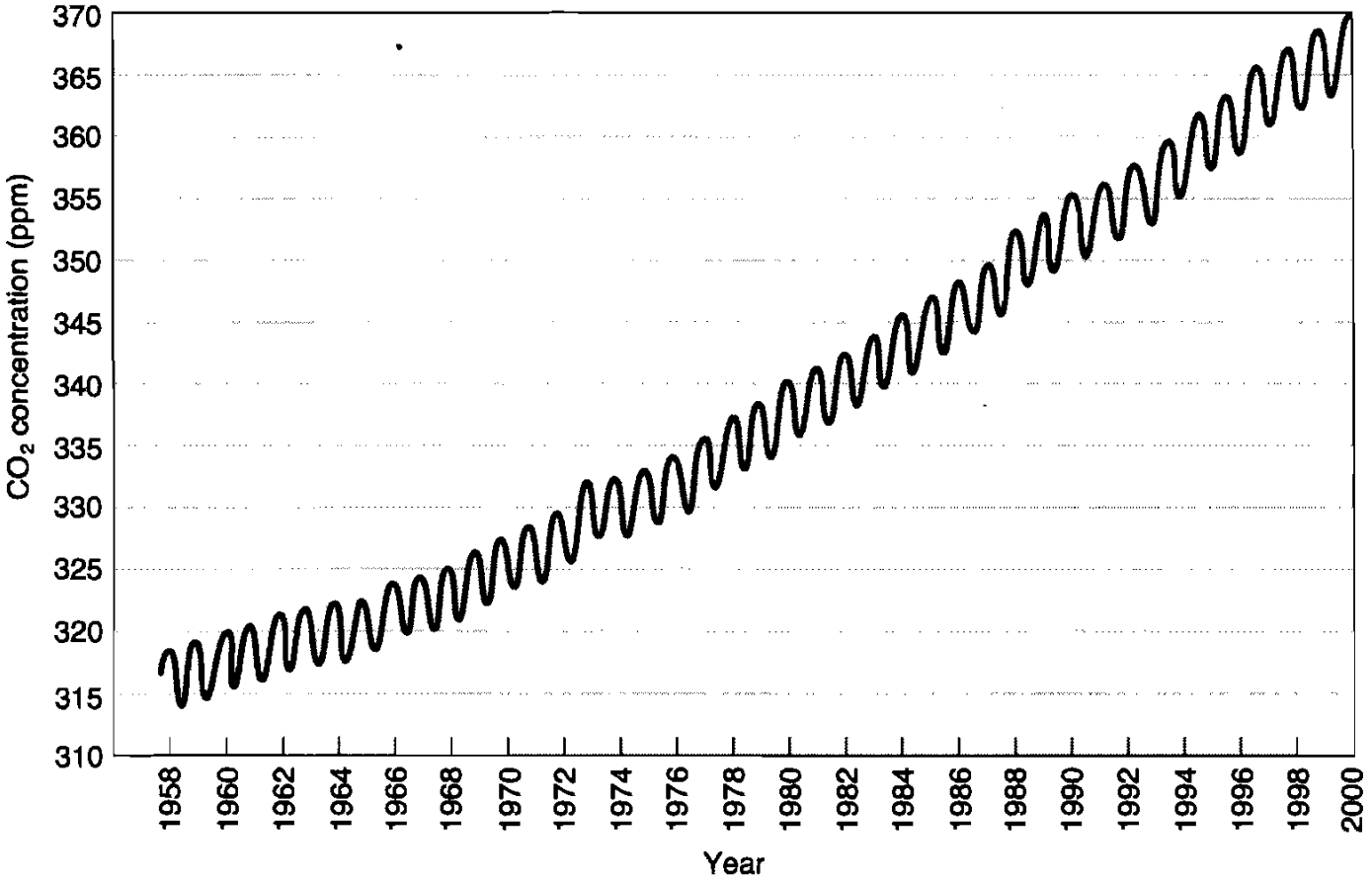


Figure 3.10 Because the first measurements were made at Mauna Loa, Hawaii, in 1958, the carbon dioxide concentration in the atmosphere has risen dramatically. The yearly seasonal variations are caused by the removal of carbon dioxide from the atmosphere by growing plants in the summer and the return of carbon dioxide to the atmosphere in the winter when plants decay.

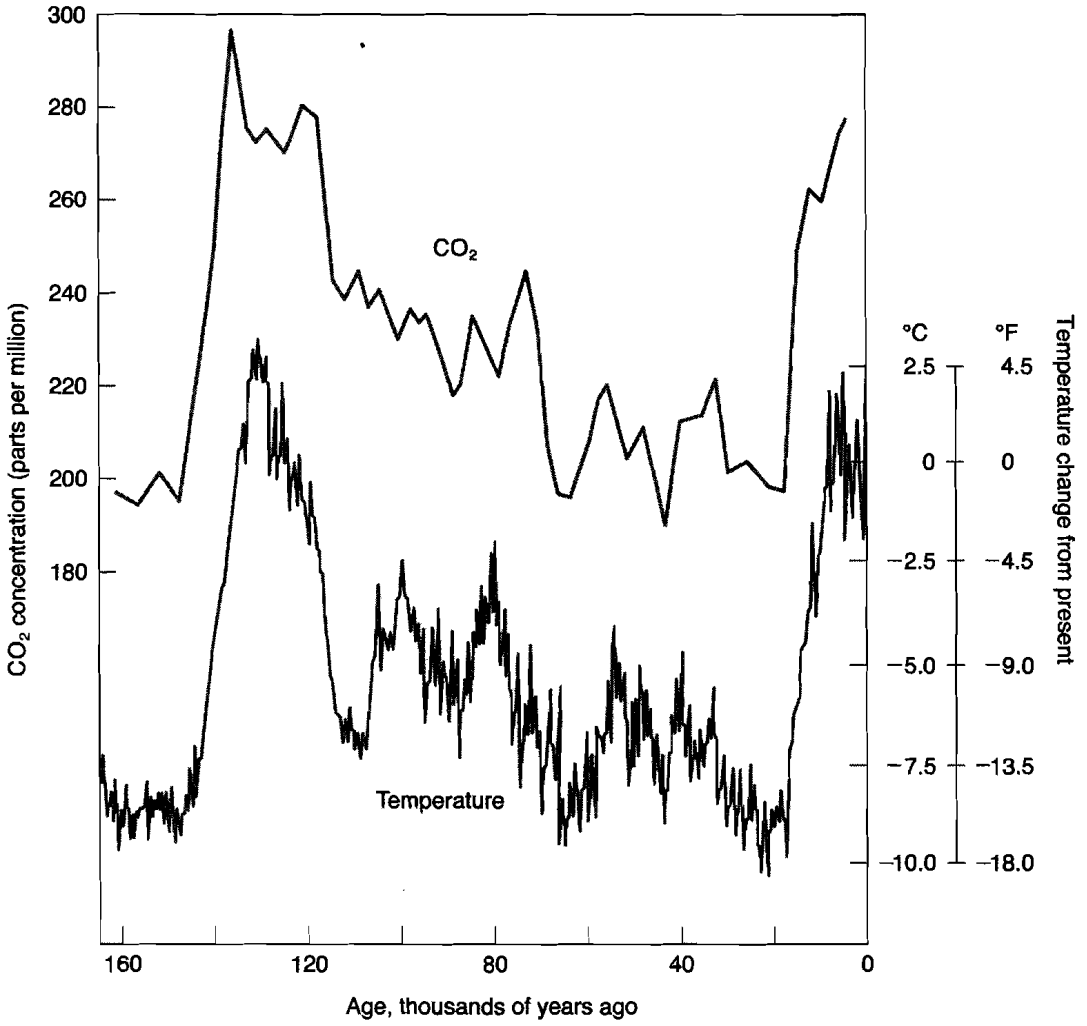
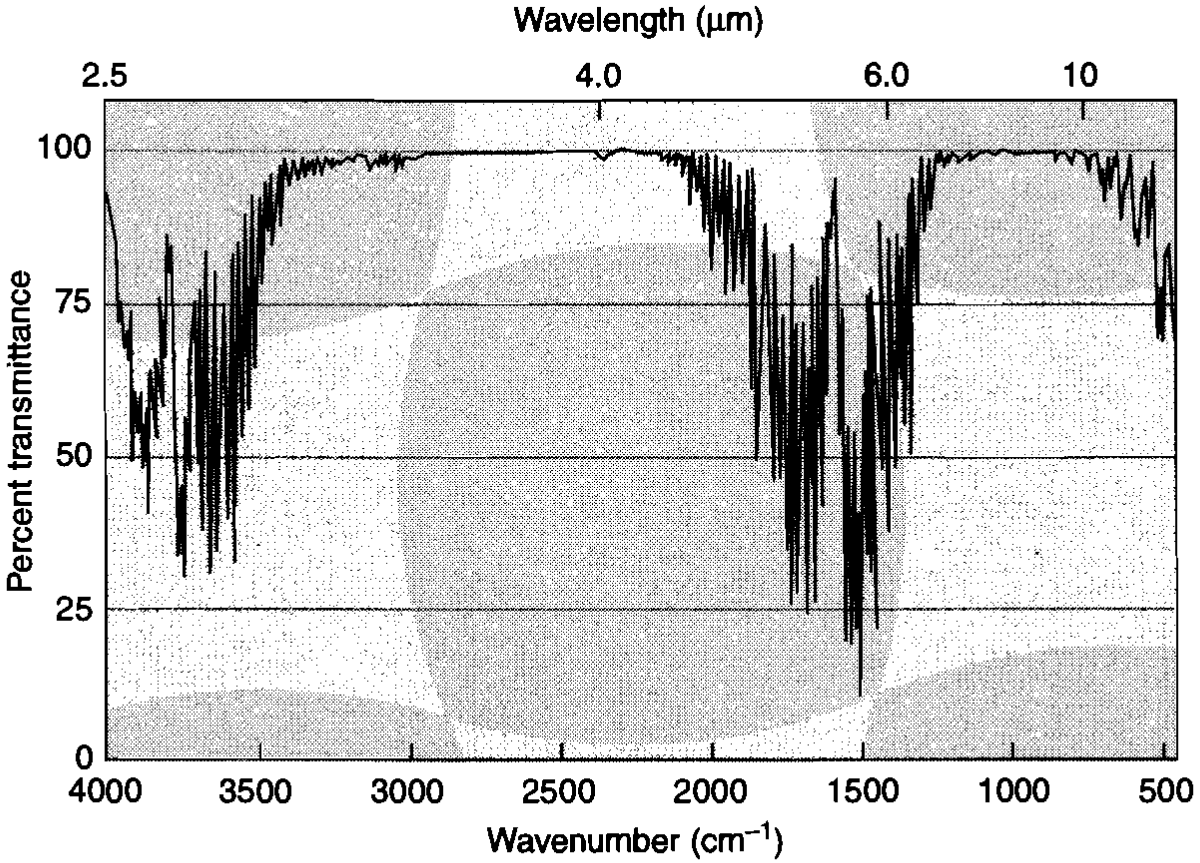


Figure 3.11 Variations in atmospheric carbon dioxide concentration and air temperature over the last 160,000 years were revealed by analysis of Antarctic ice cores. Air temperature has risen and fallen in step with increases and decreases in the carbon dioxide concentration.



3.12 Infrared absorption spectrum of water [$cm^{-1} = 10{,}000/\lambda(cm)$]. ©BIO-RAD Laboratories, Sadtler ion, 2000.

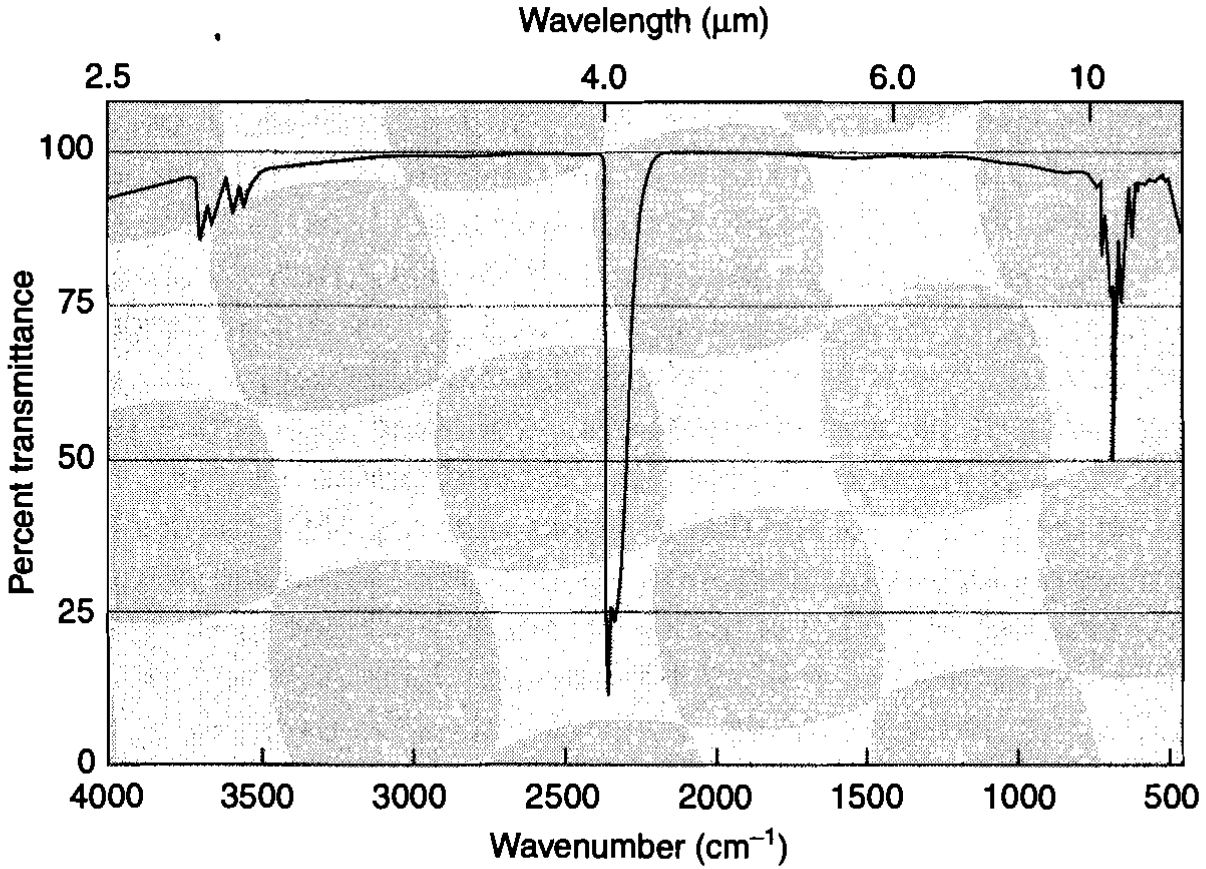


Figure 3.13 Infrared absorption spectra of carbon dioxide [$cm^{-1} = 10{,}000/\lambda(cm)$]. ©BIO-RAD Laboratories, Sadtler Division, 2000.

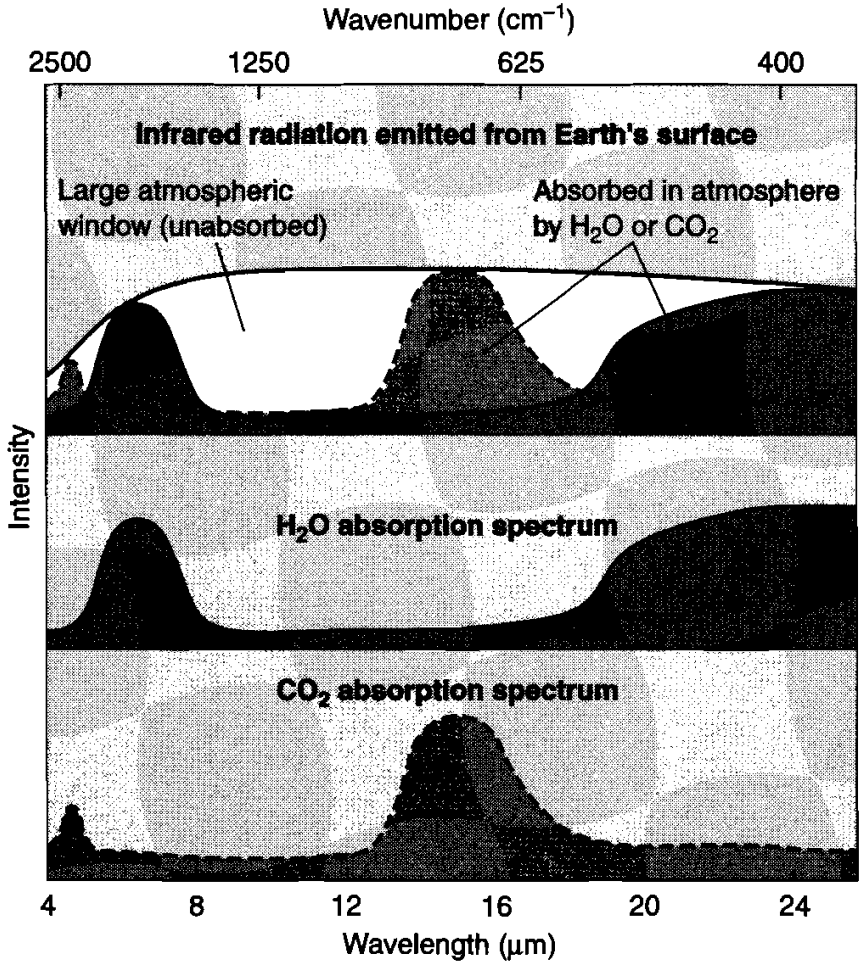


Figure 3.14 Absorption of radiation emitted from the earth's surface by carbon dioxide and water vapor.

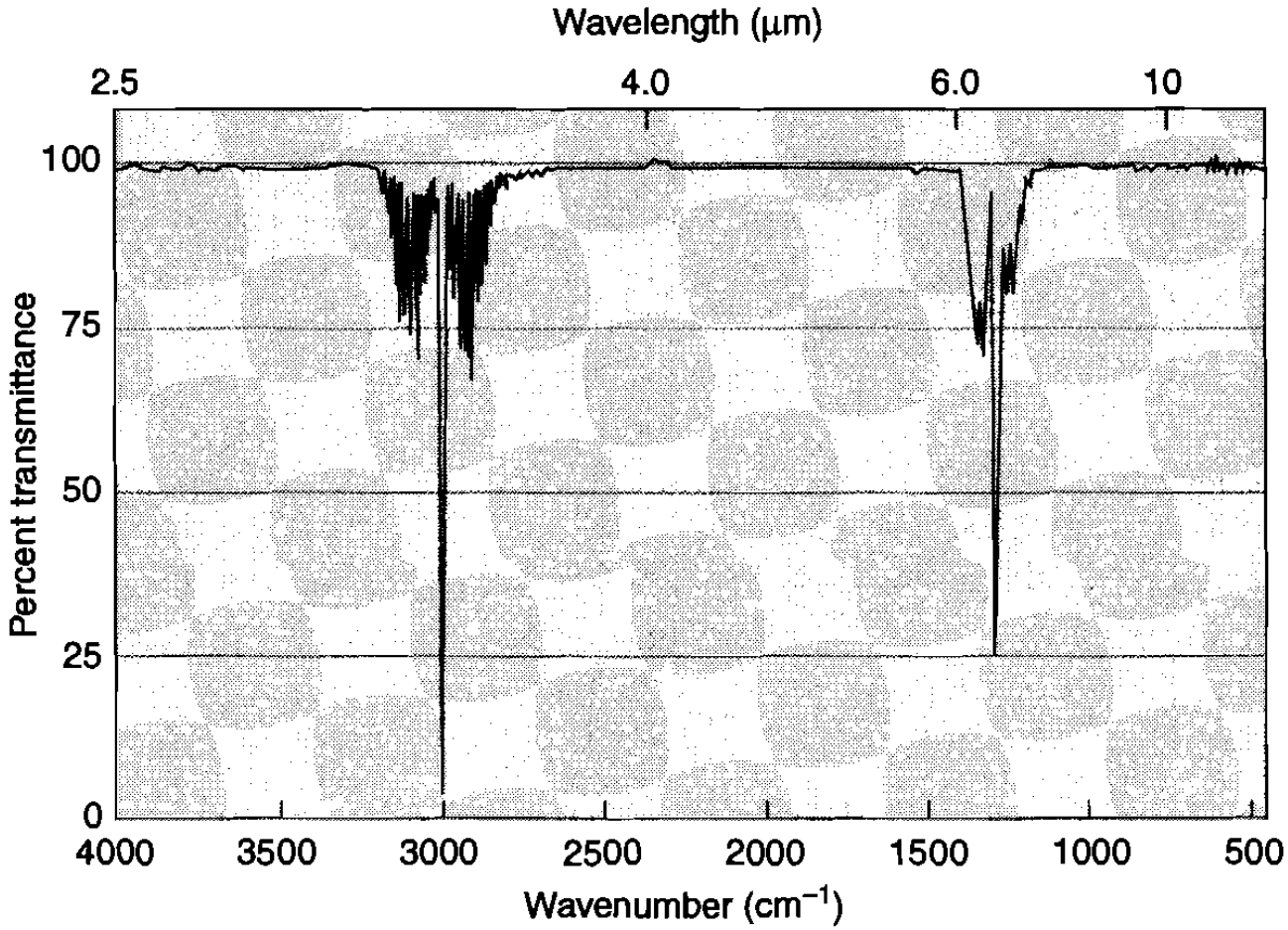
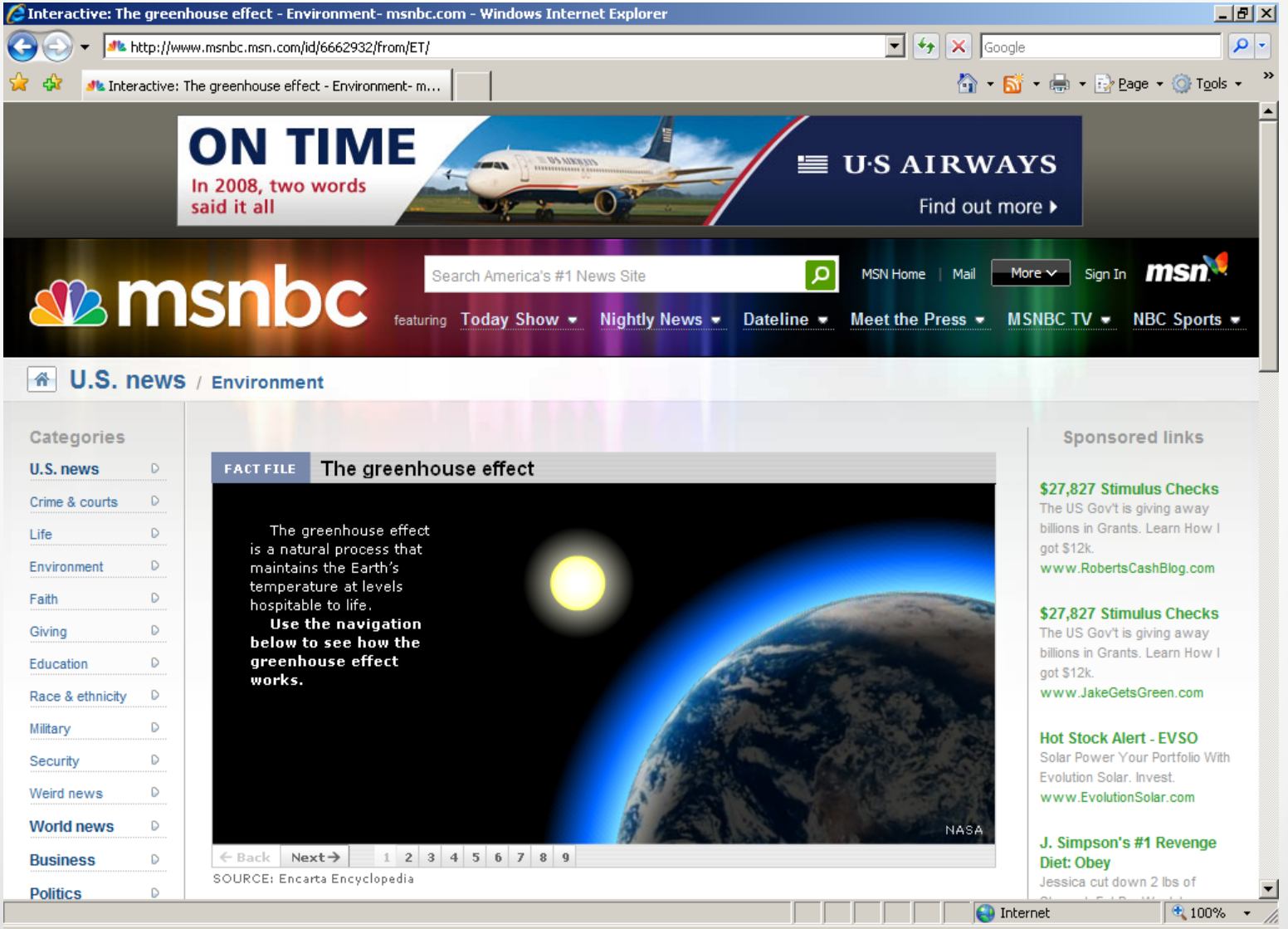


Figure 3.15 Infrared absorption spectrum of methane [$cm^{-1} = 10{,}000/\lambda(cm)$]. ©BIO-RAD Laboratories, Sadtler Division, 2000.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The greenhouse effect
The greenhouse effect is a natural process that maintains the Earth's temperature at levels hospitable to life.
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Jessica cut down 2 lbs of
Internet
100%

- **Historical CO_2 record derived from a spline fit (20 year cutoff) of the Law Dome DE08 and DE08-2 ice cores (link)**

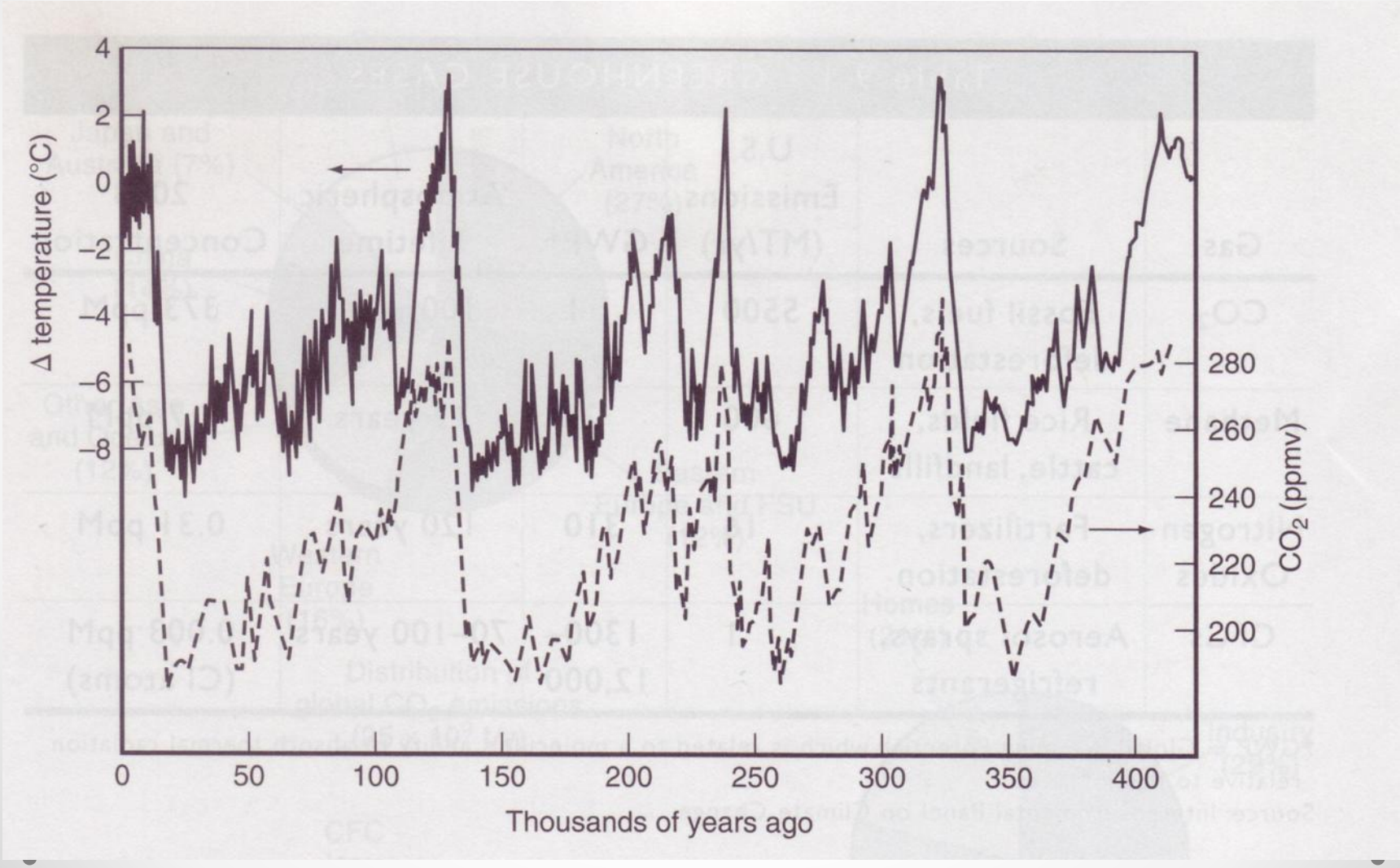
- **Wikipedia: Carbon dioxide in the Earth's atmosphere (link)**

Efficiencies of Some Energy Conversion Devices and Systems

Device	Conversion process	Efficiency
Electric generators	(mechanical -> electrical)	70-99%
Electric motor	(electrical -> mechanical)	50-90%
Gas furnace	(chemical -> thermal)	70-95%
Wind turbine	(mechanical -> electrical)	35-50%
Fossil fuel power plant	(chemical -> thermal -> mechanical -> electrical)	30-40%
Nuclear power plant	(nuclear -> thermal -> mechanical -> electrical)	30-35%
Automobile engine	(chemical -> thermal -> mechanical)	20-30%
Fluorescent lamp	(electrical -> light)	20%
Incandescent lamp	(electrical -> light)	5%
Solar cell	(light -> electrical)	5-28%
Fuel cell	(chemical -> electrical)	40-60%

"Energy: Its Use and the Environment", 4th Ed. **2006**

Correlation between carbon dioxide concentrations and the earth's temperature over the past 400,000 years



Global concentration of methane gas over the past 1,000 years

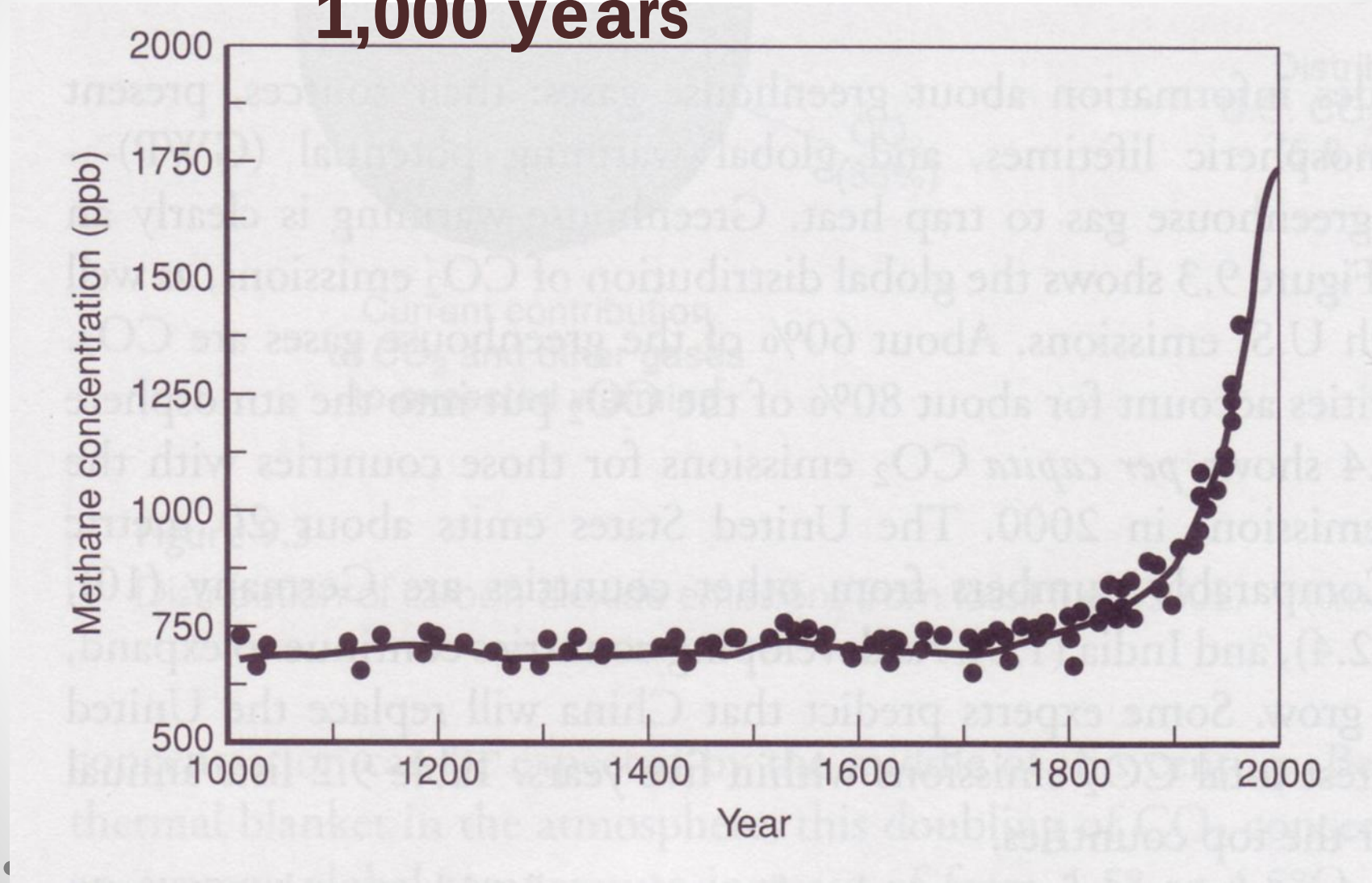


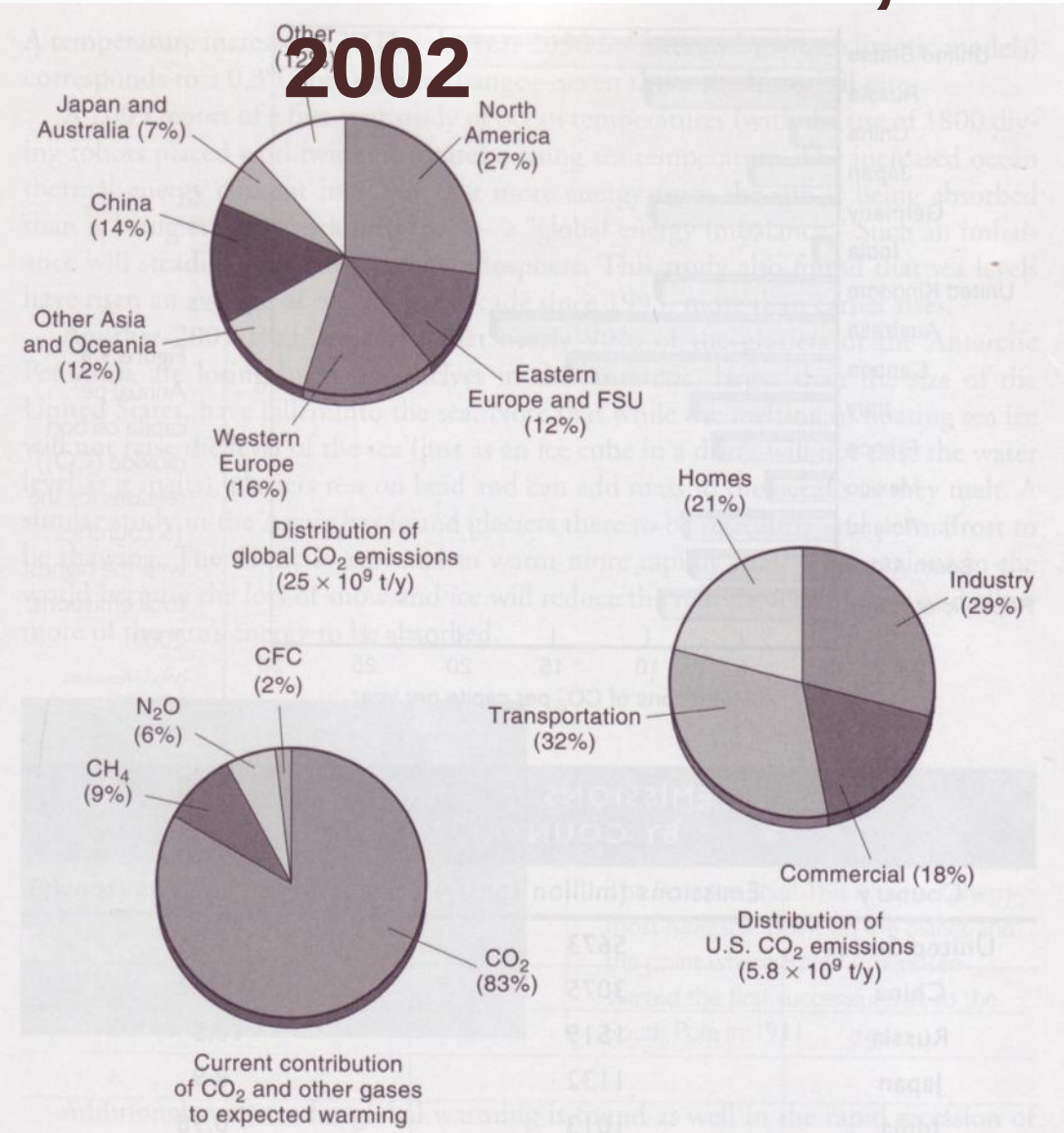
Table 9.1 GREENHOUSE GASES

Gas	Sources	U.S. Emissions (MT/yr)	GWP*	Atmospheric Lifetime	2003 Concentration
CO_2	Fossil fuels, deforestation	5500	1	100 years	373 ppM
Methane	Rice fields, cattle, landfills	600	21	12 years	1.7 ppM
Nitrogen Oxides	Fertilizers, deforestation	16	310	120 years	0.31 ppM
CFCs	Aerosol sprays, refrigerants	1	1300–12,000	70–100 years	0.003 ppM (Cl atoms)

*GWP = Global Warming Potential, which is related to a molecule's ability to absorb thermal radiation relative to that of CO_2.

Source: Intergovernmental Panel on Climate Change.

Distribution of carbon dioxide emissions from fossil fuels, 2002



Annual per capita carbon dioxide (CO_2) releases for the 15 countries with the highest total emissions, 2000.

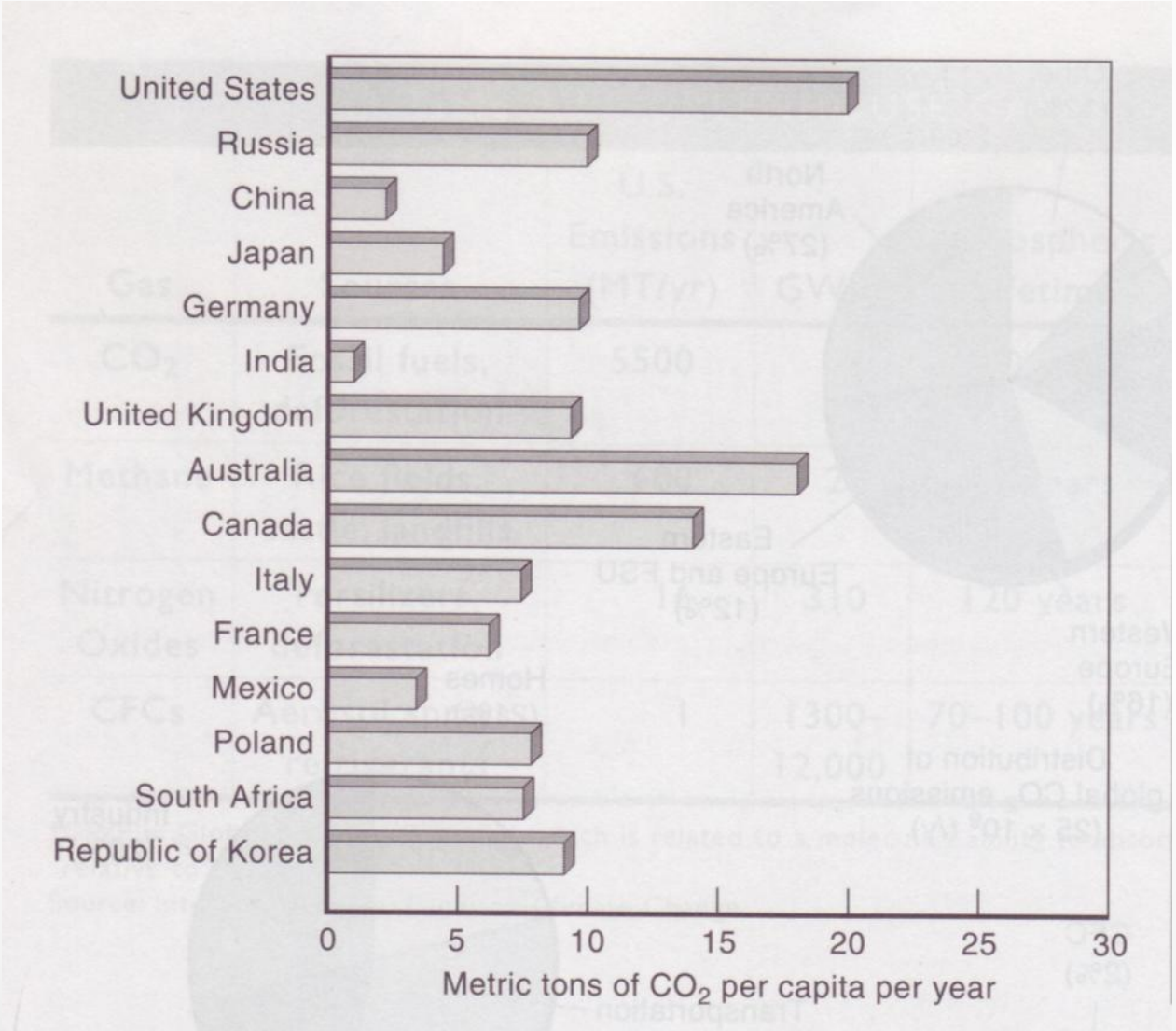
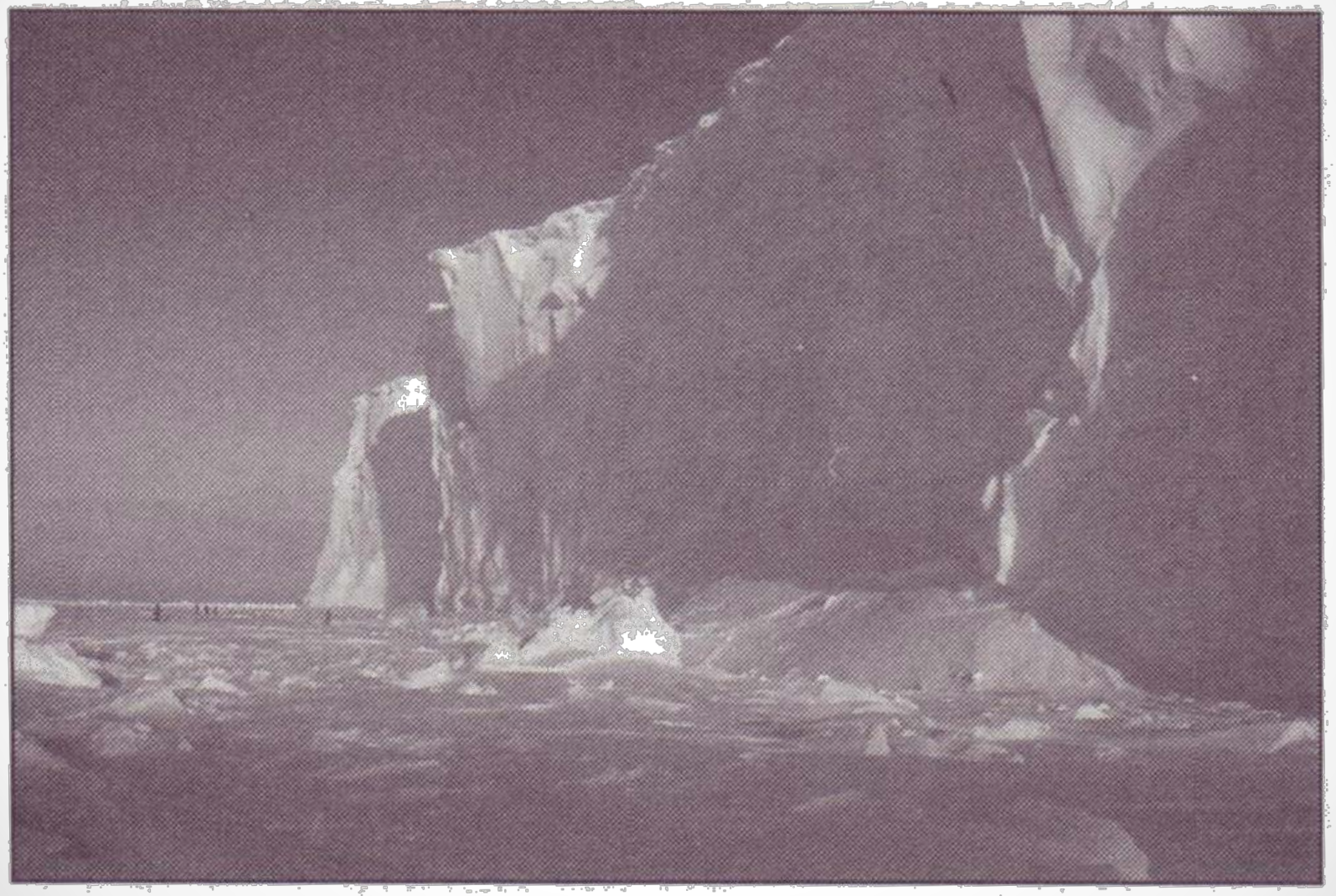


Table 9.2 EMISSIONS OF CARBON DIOXIDE, BY COUNTRY, 2002

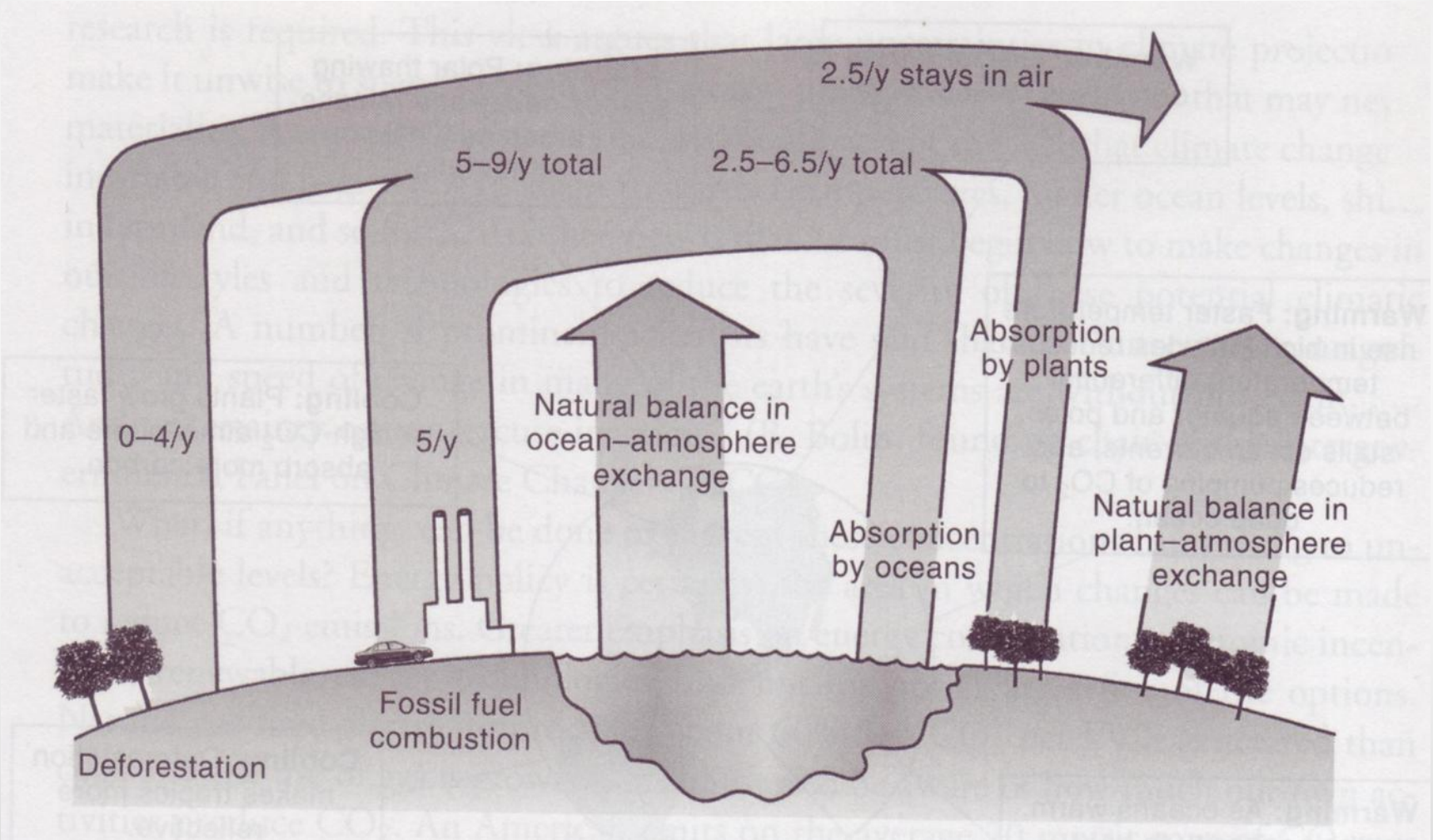
Country	Emissions (million tons/y)	Per Capita Emissions (tons/y)
United States	5673	19.8
China	3075	2.42
Russia	1519	10.5
Japan	1132	8.9
India	1013	0.98
Germany	850	10.3
United Kingdom	541	9.2
Canada	520	16.7
Republic of Korea	436	9.2
Italy	425	7.3
Ukraine	343	7.2
France	363	6.2
Poland	302	7.8
Mexico	425	3.4
Australia	345	18

Source: Oak Ridge National Laboratory.

Ross Ice Shelf



Carbon cycle of the earth



Potential feedbacks to global warming

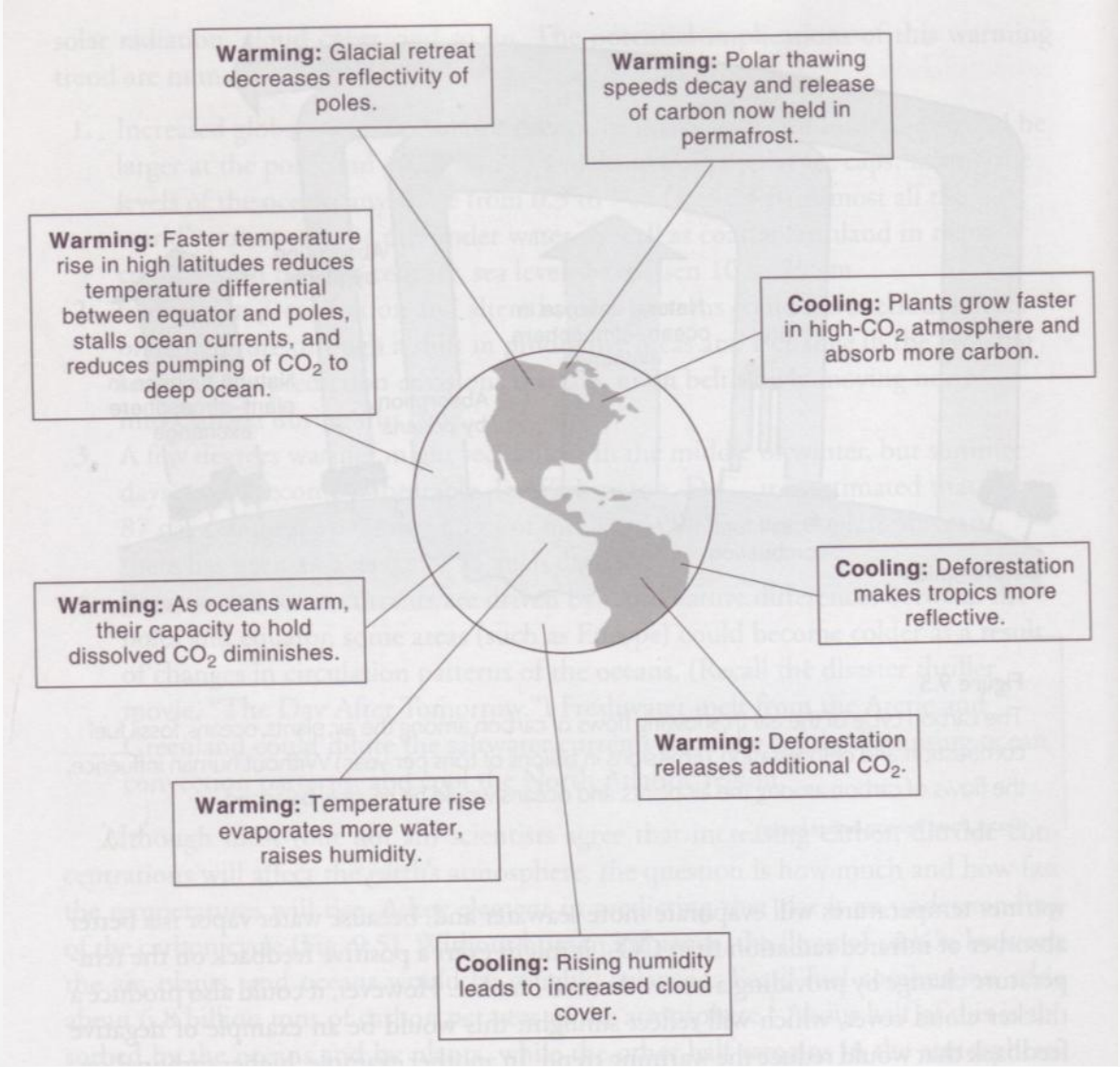


Table 9.3 INDIVIDUAL CARBON DIOXIDE PRODUCTION

Use	Basis	CO_2 Emissions (lb)
Automobile	Per gallon	20
Electricity	Per kWh (using coal)	2
Natural gas	Per therm (for heating)	12

Variations in temperature, CO2, and dust from the Vostok ice core over the last 400,000 years