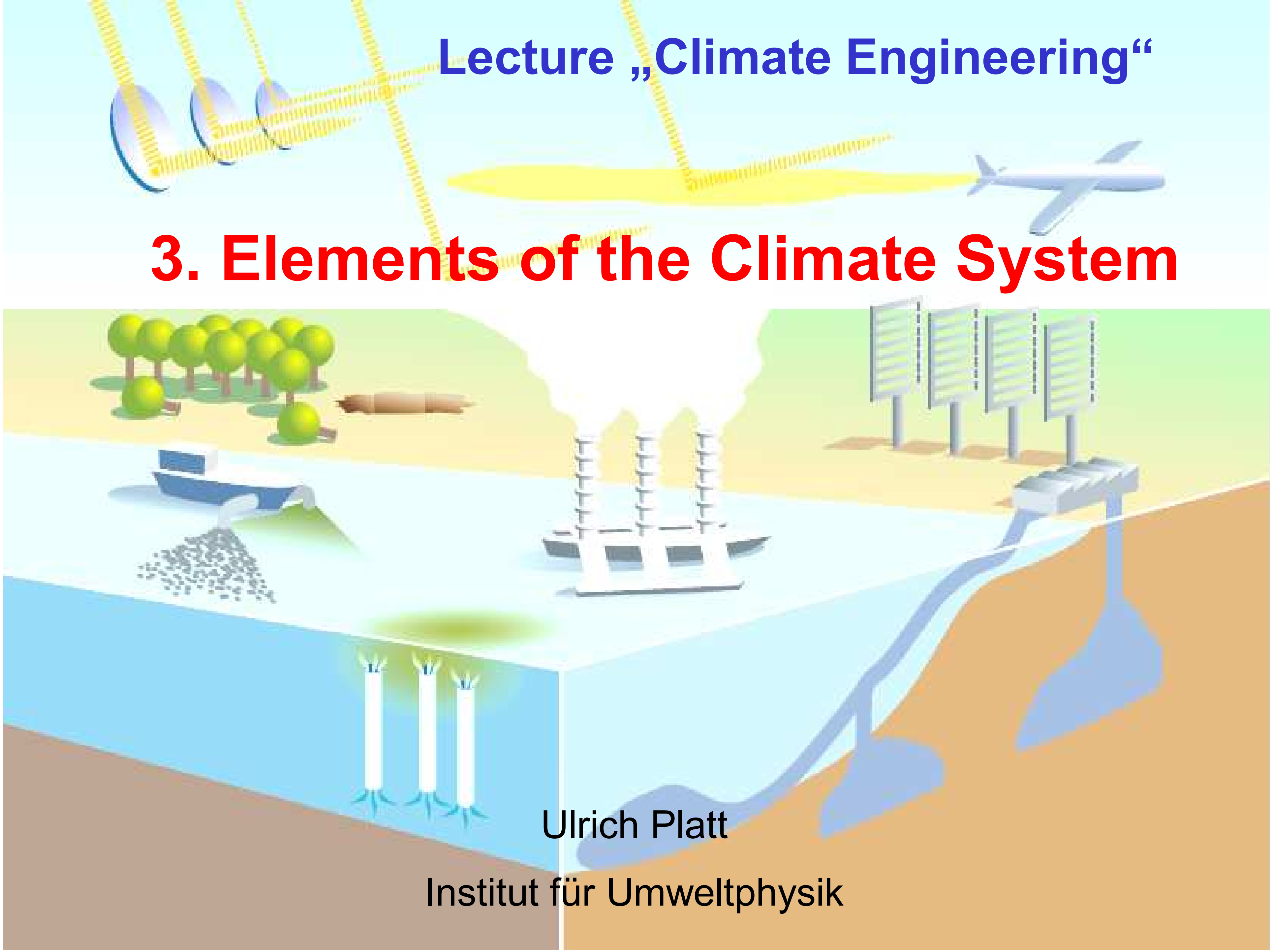
Lecture „Climate Engineering“

3. Elements of the Climate System



Ulrich Platt

Institut für Umweltphysik

Lecture Program of „Climate Engineering“

Part 1: Introduction to the Climate System (4 sessions)

1. Introduction and scope of the lecture
2. The Climate System – Radiation Balance
3. Elements of the Climate System – Greenhouse gases, Clouds, Aerosol
4. Climate System: Sensitivity, Predictions

Part 2: Climate Engineering Methods – SRM (4 sessions)

1. SRM – Reflectors in space
2. SRM – Aerosol in the Stratosphere
3. SRM – Cloud Whitening
4. SRM – Anything else

Part 3: Climate Engineering Methods – CDR (4 sessions)

1. Direct (Carbon dioxide) removal from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization
4. Other greenhouse gases

Part 4: CE – Effectiveness, Side Effects (3 sessions)

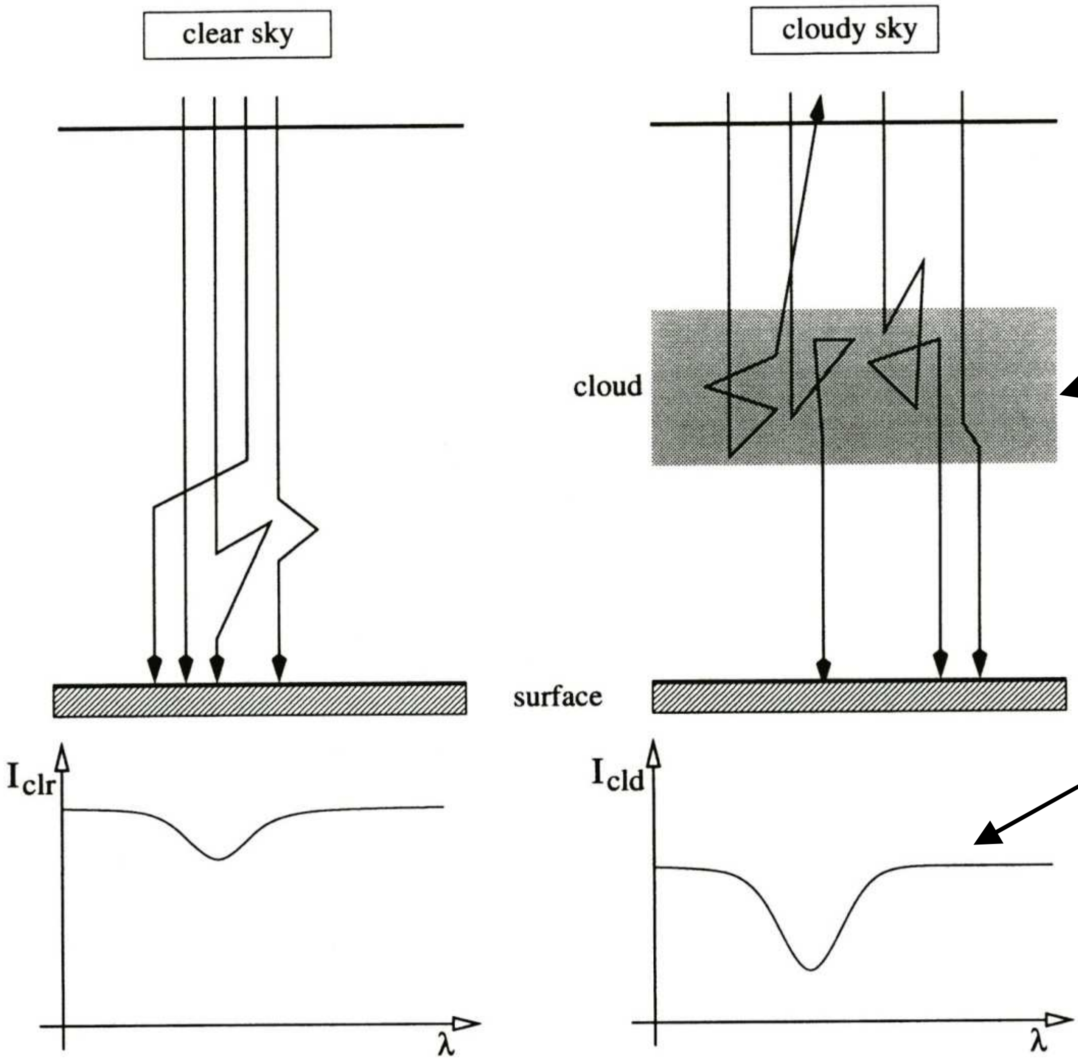
1. Comparison of Techniques, characterisation of side effects
2. Other parameters than temperature
3. Summary

Contents of Today's Lecture

Greenhouse gases, Clouds, Aerosol

- scattering – molecules and aerosols
- climate influences of clouds
- The importance of greenhouse gases
- CO_2 cycle
- Carbon budgets

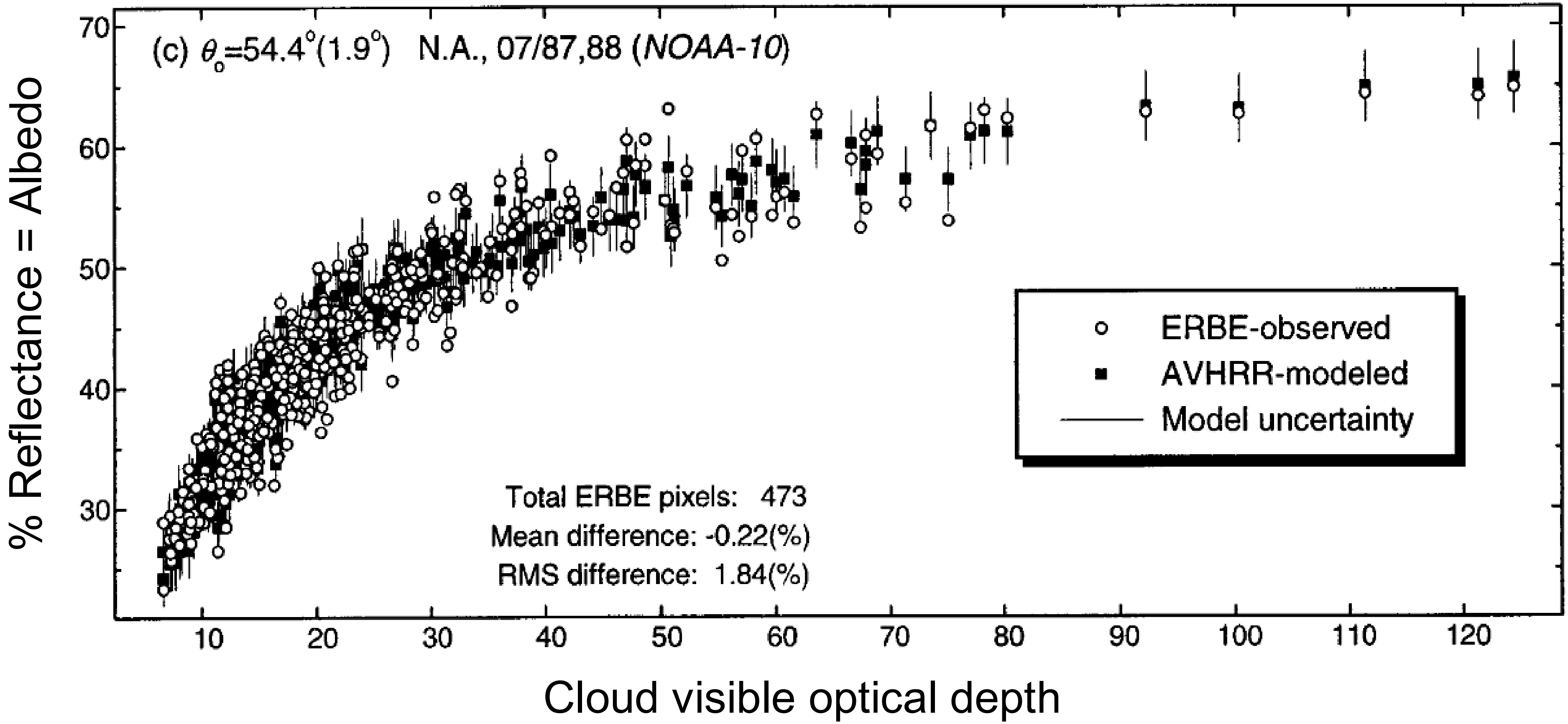
Radiation in the Atmosphere – Impact of Aerosol and Clouds



Much longer Light-Path due to multiple scattering

O_2-Absorption Line

Cloud Reflectance as Function of Cloud Optical Depth

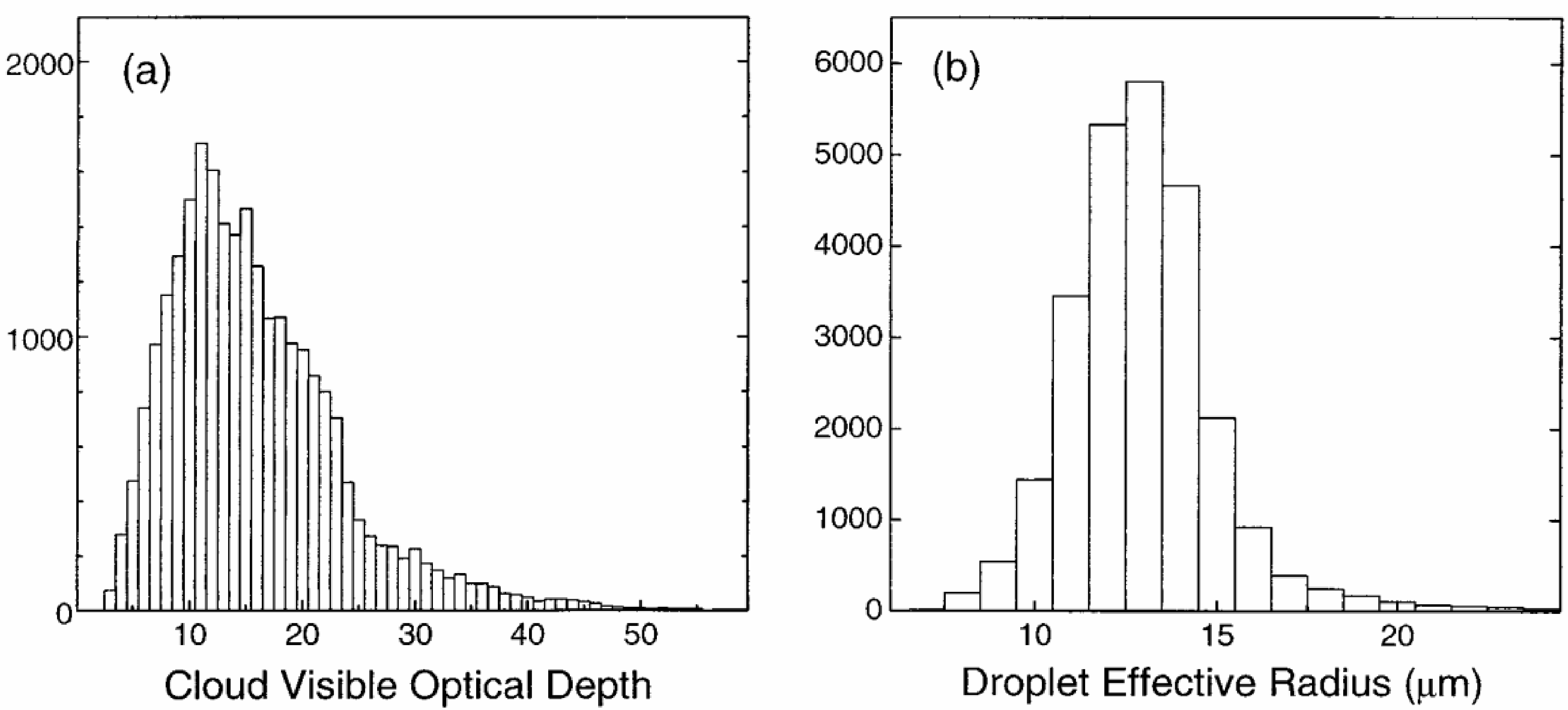


Cloud Optical Depth = Vertical Optical Density τ_{cloud}

$$I_{direct} = I_0 \cdot e^{-\tau_{cloud}} \Leftrightarrow \ln\left(\frac{I_0}{I_{direct}}\right)\tau_{cloud} = \ln\left(\frac{I_0}{I_{direct}}\right)$$

Fu-Lung Chang, Zhanqing Li, and Steven. A. Ackermann (2000), Examining the Relationship between Cloud and Radiation Quantities Derived from Satellite Observations and Model Calculations, J. Climate 13, 3842-3859.

Global Cloud Statistics from Satellite Observation

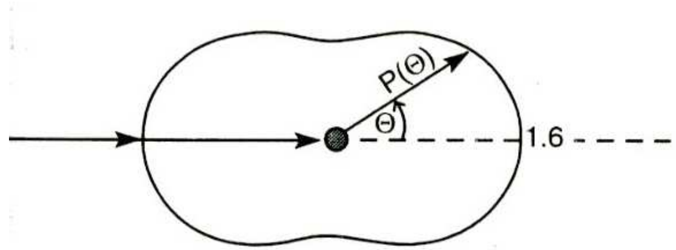


Fu-Lung Chang, Zhanqing Li, and Steven. A. Ackermann (2000), Examining the Relationship between Cloud and Radiation Quantities Derived from Satellite Observations and Model Calculations, J. Climate 13, 3842-3859.

Types of (approximately) elastic Scattering

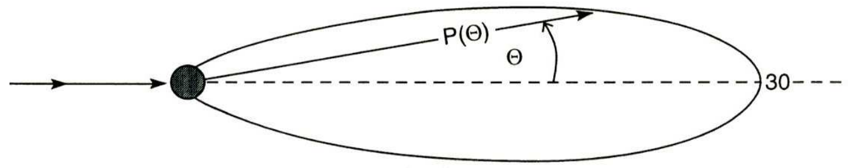
Rayleigh scattering: scattering on air molecules

– radius of scatterers r << λ
– SW radiation (λ ≈ 100s of nm) and gas molecules (r ≈ 0.1 nm)



Mie scattering: Scattering on particles, aerosols, droplets

– radius of scatterers r ≥ λ
– SW radiation and aerosol particles or droplets (100 nm < r < 50 μm)



Size parameter x to compare particle size and wavelength of light:

$$x = \frac{2\pi r}{\lambda}$$

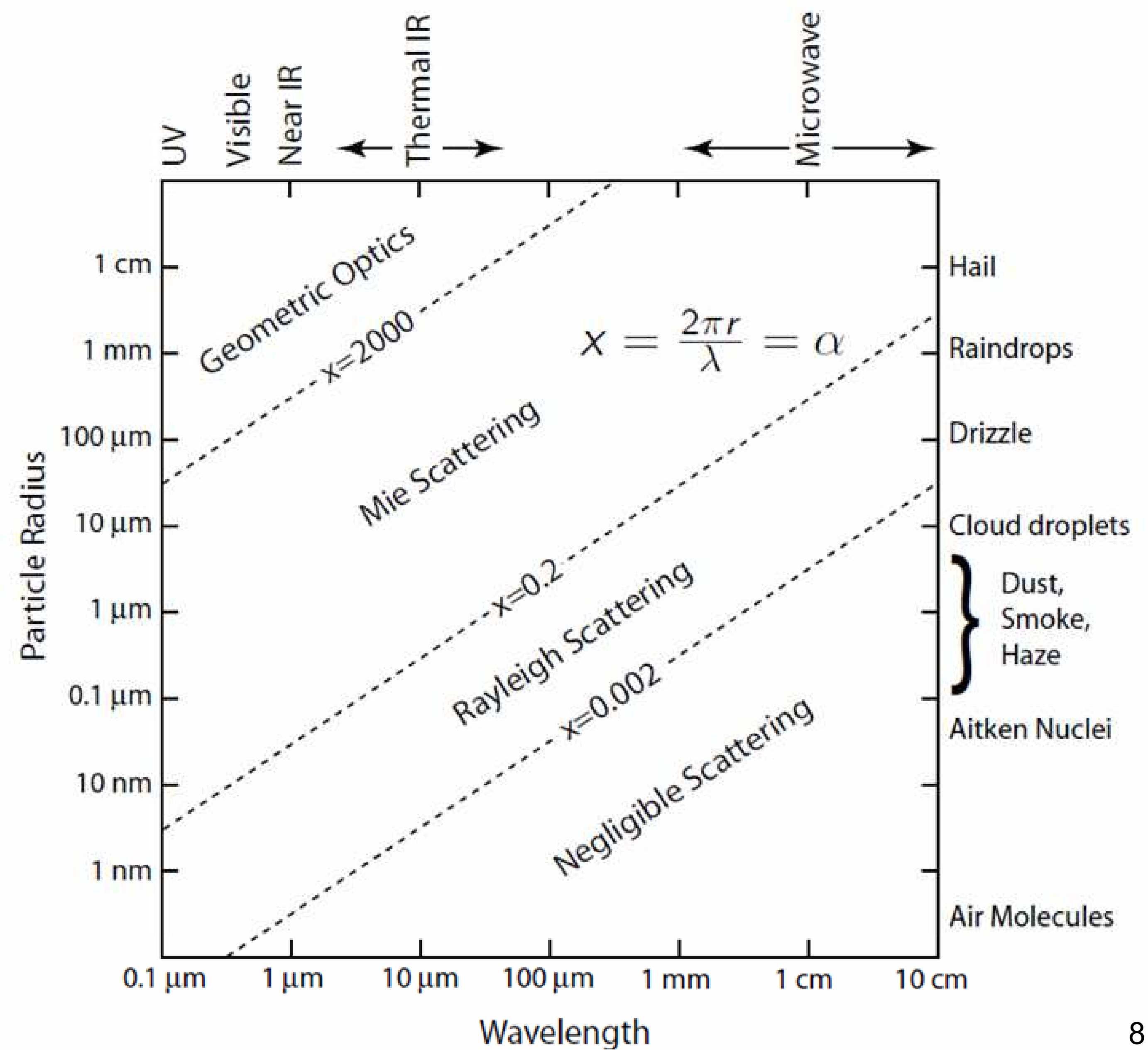
x << 1 for molecules and fine particles: Rayleigh Scattering

x ≥ 1 for coarse particles and clouds: Mie Scattering

Scattering Regimes

Clouds

Aerosol

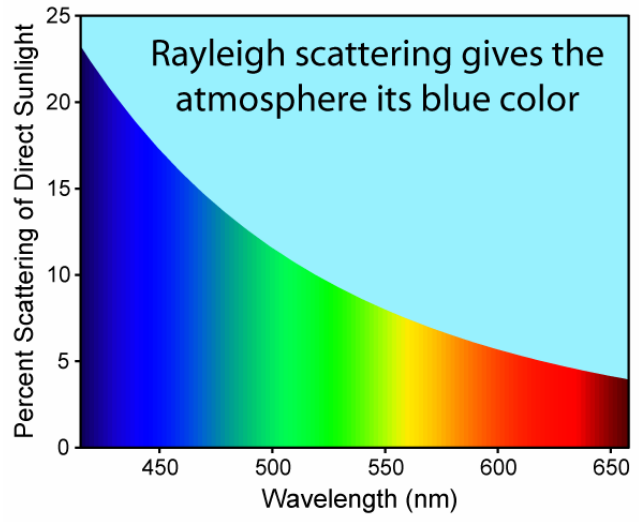


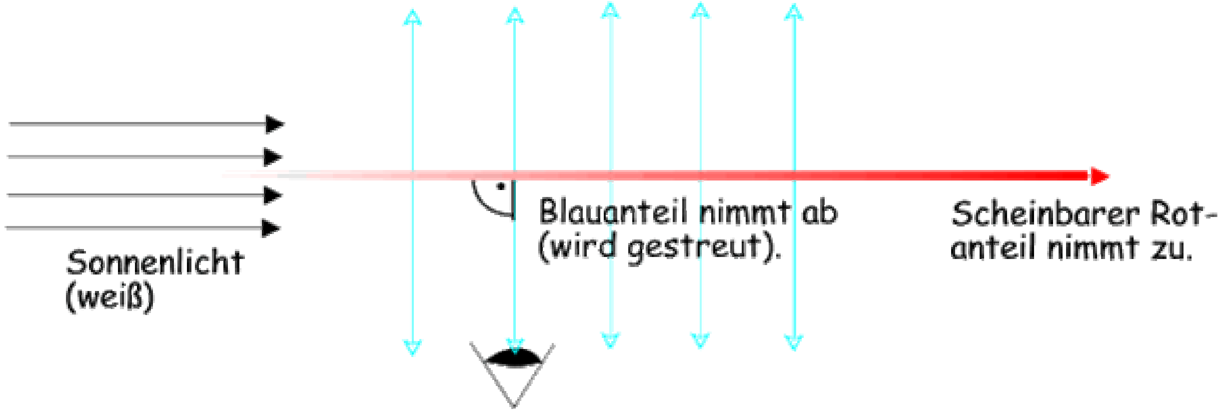
Petty, 2006. A first course in atmospheric radiation, Sundog Publishing

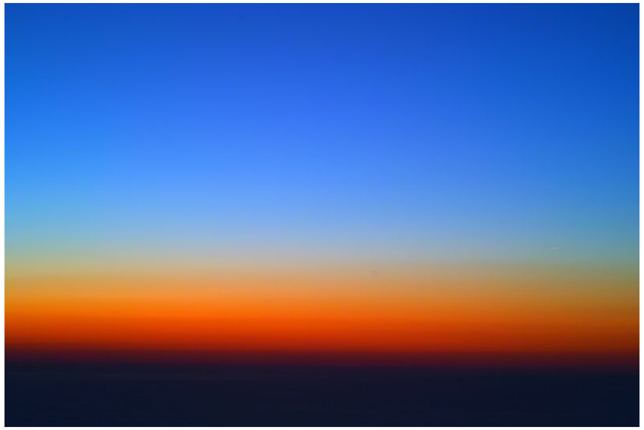
Consequences of Rayleigh Scattering

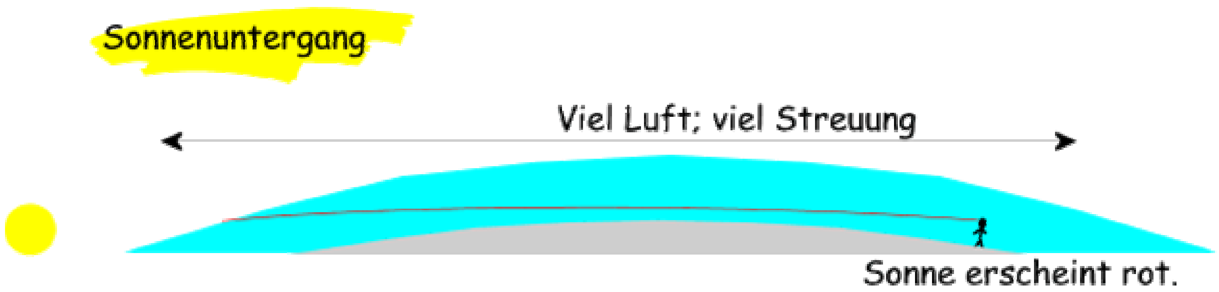
Presence of diffuse radiation, i.e. the sky is not black

- the sky is blue – due to preferred scattering of short (blue) wavelengths
- Sunrise/sunset: sky is red due to preferred transmission of long waves









Mie Scattering

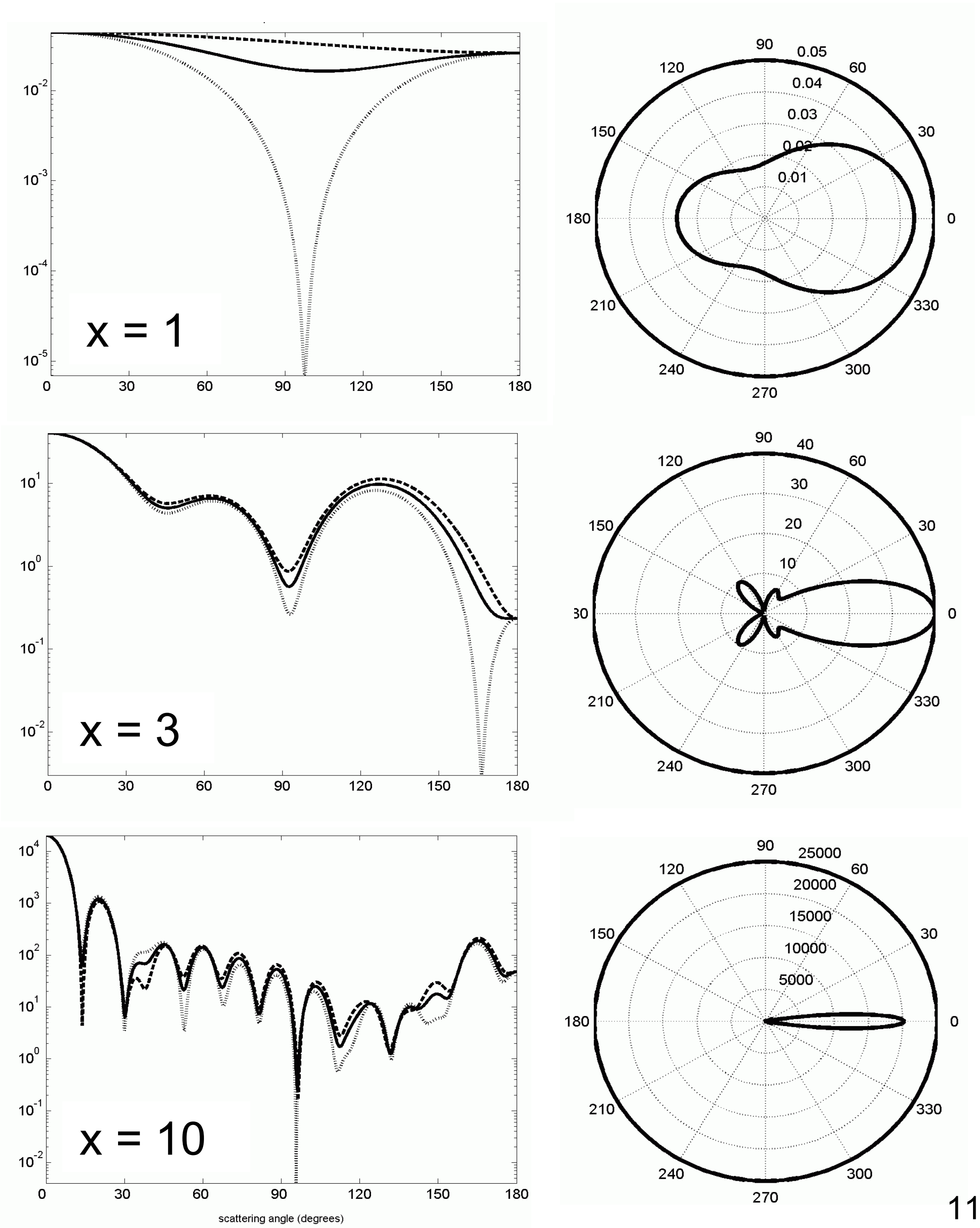
- Radius of scatterer > wavelength
- coherent excitation of a large number of elementary emitters (= particles)
- no analytical solution
- properties of scattered light:
  - weak wavelength dependence, $\sigma_M \sim \lambda^{-\alpha}$ with $\alpha \approx 1.3$ (Ångström exponent)
  - strong forward scattering (caused by interferences)
  - strong size dependence

- consequence of Mie scattering:
  - sky gets whitish for high particle loadings (smaller wavelength dependence than Rayleigh scattering)

Mie-Scattering phase functions

Size Parameter:

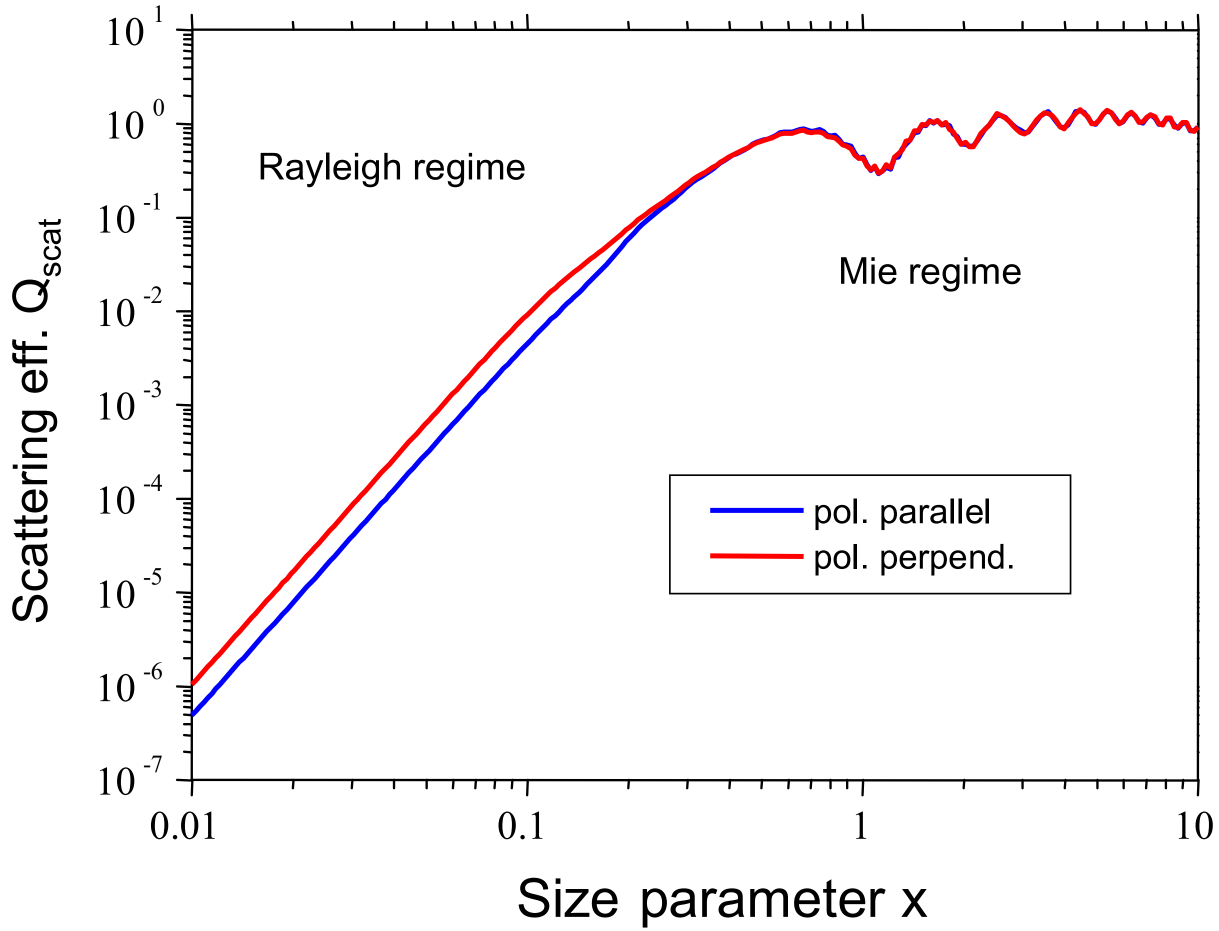
$$x = \frac{2\pi r}{\lambda}$$



Scattering Efficiency

Scattering coefficient or efficiency compares scattering cross-section to geometrical cross-section:

$$Q_{scat} = \frac{\sigma_{scat}}{\pi r^2}$$

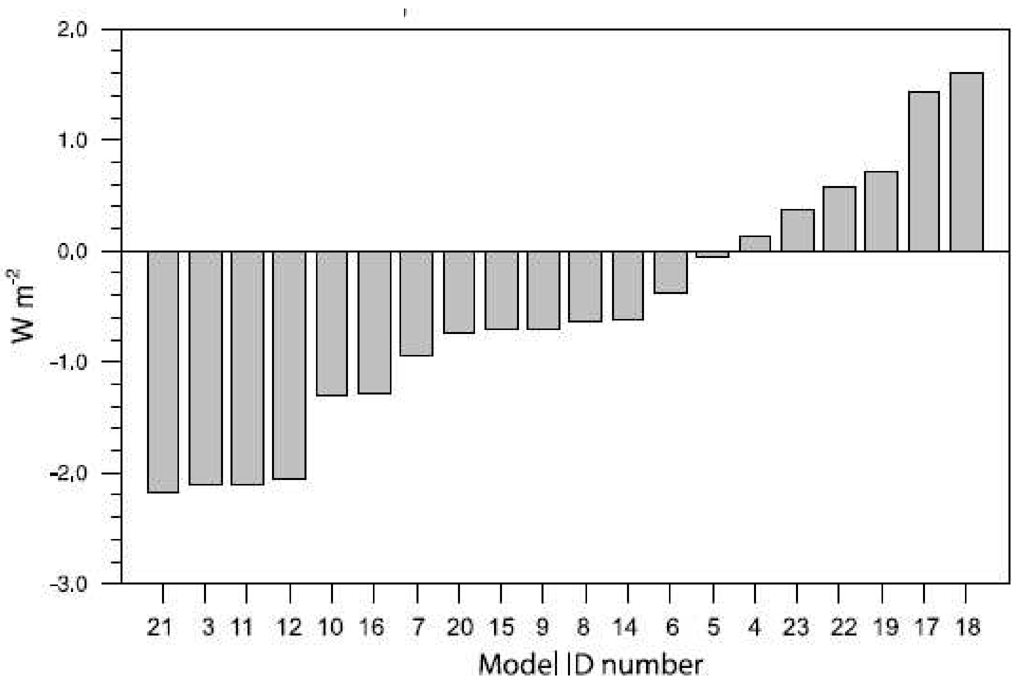


Change in Cloud Forcing (1980-1999 vs. 2080-2099) Predicted by Different Models

General rule:

Low clouds tend to cool
High clouds tend to warm

Main question:
Does cloud cover and/or distribution change when climate changes?



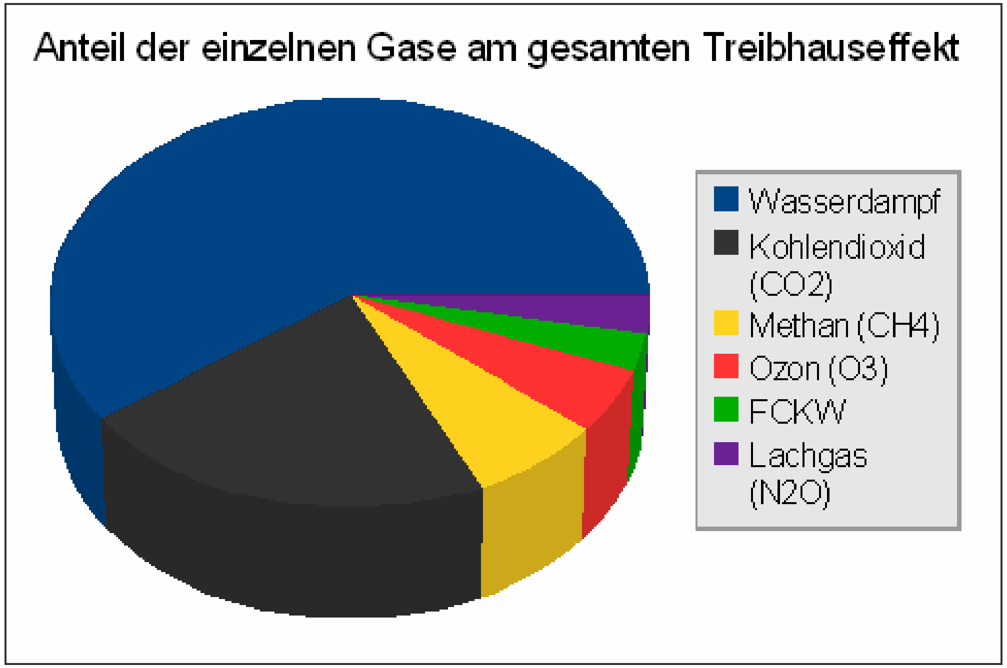
Changes in global mean cloud radiative forcing (Wm^{-2}) for the period 1980-1999 vs. 2080-2099

IPCC 2007

Greenhouse Gases

Greenhouse gases (GHG) are gases that can absorb and emit (thermal infrared radiation.
Most abundant (and most important) GHG in Earth's atmosphere:

1) water vapour (H_2O)
2) carbon dioxide (CO_2)
3) methane (CH_4)
4) ozone (O_3)
5) nitrous oxide (N_2O)



Contribution of most important **anthropogenic+natural** greenhouse gases to the **total greenhouse effect** (today)

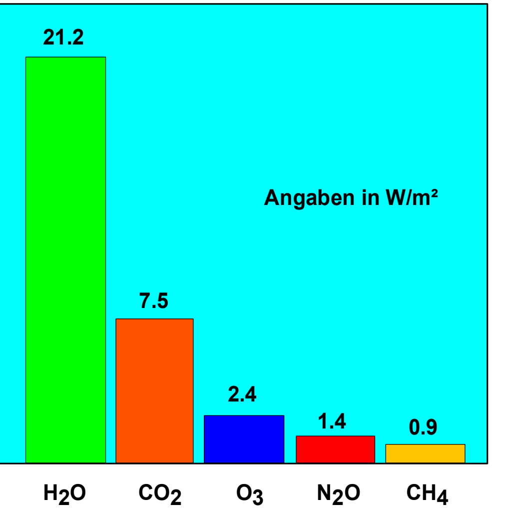
Atmospheric concentrations of greenhouse gases are determined by balance between sources (emissions of the gas from human activities and natural systems) and sinks (the removal of the gas from the atmosphere by conversion to a different chemical compound).

The 'Natural Greenhouse Effect'

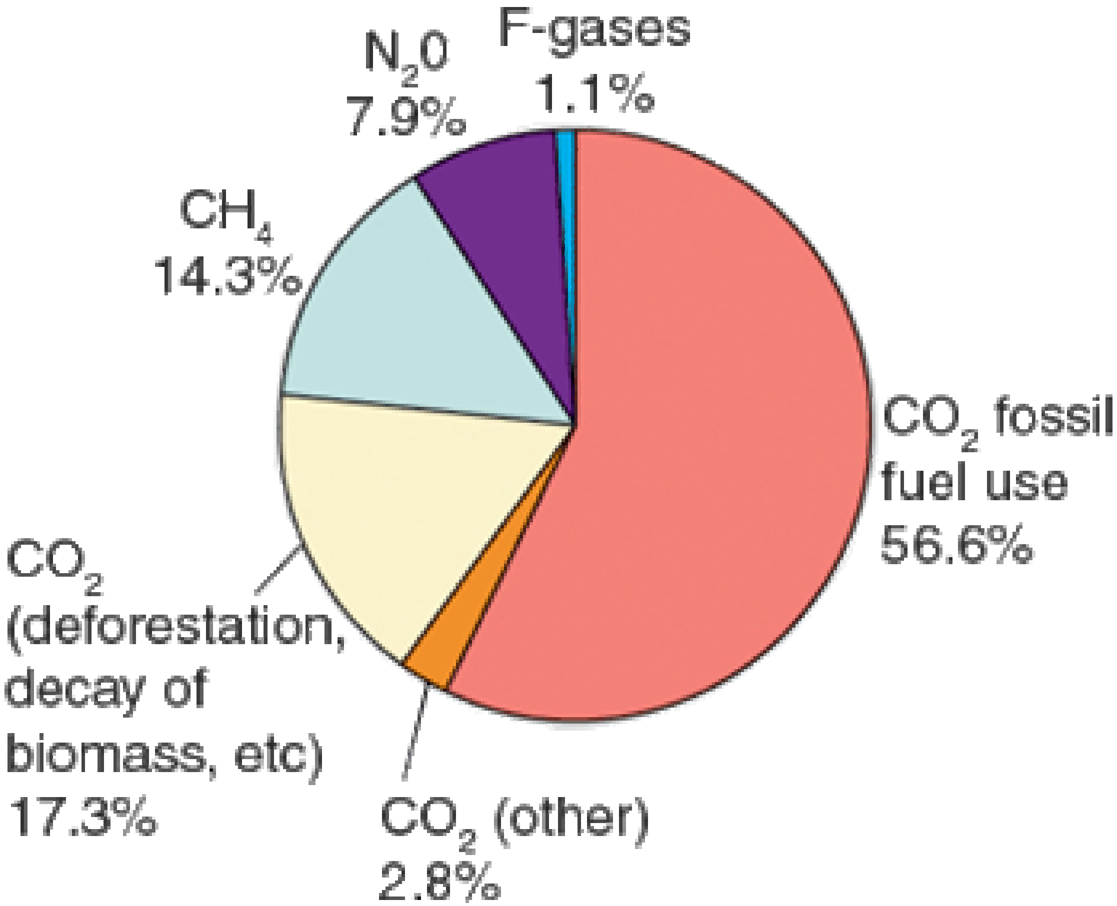
In summary the "natural' greenhouse effect amounts to about +33 K

Contribution of individual gases (after Kondratyev and Moskalenko, in J.T. Houghton (Ed.), IUP 957, 1984)

Gas	Prominent Band µm	ΔT K	%
H_2O	6.3, >16	20.6	62
CO_2	13 - 17	7.2	22
O_3 (in the troposphere)	9.6	2.4	7
N_2O	4.8, 7.8	1.4	4
CH_4	3.4, 7.3	0.8	2.5



Anthropogenic Greenhouse Gases



Contribution of most important **anthropogenic** greenhouse gases to global warming
Source: IPCC-2007

IPCC List of Greenhouse Gases

	Mixing ratio (ppt, if not given) and changes		Radiative Forcing	
Species	**2005**	**Change since 1998**	**2005 ($W\ m^{-2}$)**	**Change since 1998 (%)**
CO_2	379 ± 0.65 ppm	+13 ppm	1.66	+13
CH_4	1,774 ± 1.8 ppb	+11 ppb	0.48	-
N_2O	319 ± 0.12 ppb	+5 ppb	0.16	+11
CFC-11	251 ± 0.36 ppt	–13 ppt	0.063	–5
CFC-12	538 ± 0.18 ppt	+4 ppt	0.17	+1
CFC-113	79 ± 0.064 ppt	–4 ppt	0.024	–5
HCFC-22	169 ± 1.0 ppt	+38 ppt	0.033	+29
HCFC-141b	18 ± 0.068 ppt	+9 ppt	0.0025	+93
HCFC-142b	15 ± 0.13 ppt	+6 ppt	0.0031	+57
CH_3CCl_3	19 ± 0.47 ppt	–47 ppt	0.0011	–72
CCl_4	93 ± 0.17 ppt	–7 ppt	0.012	–7
HFC-125	3.7 ± 0.10 ppt	+2.6 ppt	0.0009	+234
HFC-134a	35 ± 0.73 ppt	+27 ppt	0.0055	+349
HFC-152a	3.9 ± 0.11 ppt	+2.4 ppt	0.0004	+151
HFC-23	18 ± 0.12 ppt	+4 ppt	0.0033	+29
SF_6	5.6 ± 0.038 ppt	+1.5 ppt	0.0029	+36
CF_4 (PFC-14)	74 ± 1.6 ppt	-	0.0034	-
C_2F_6 (PFC-116)	2.9 ± 0.025	+0.5	0.0008	+22

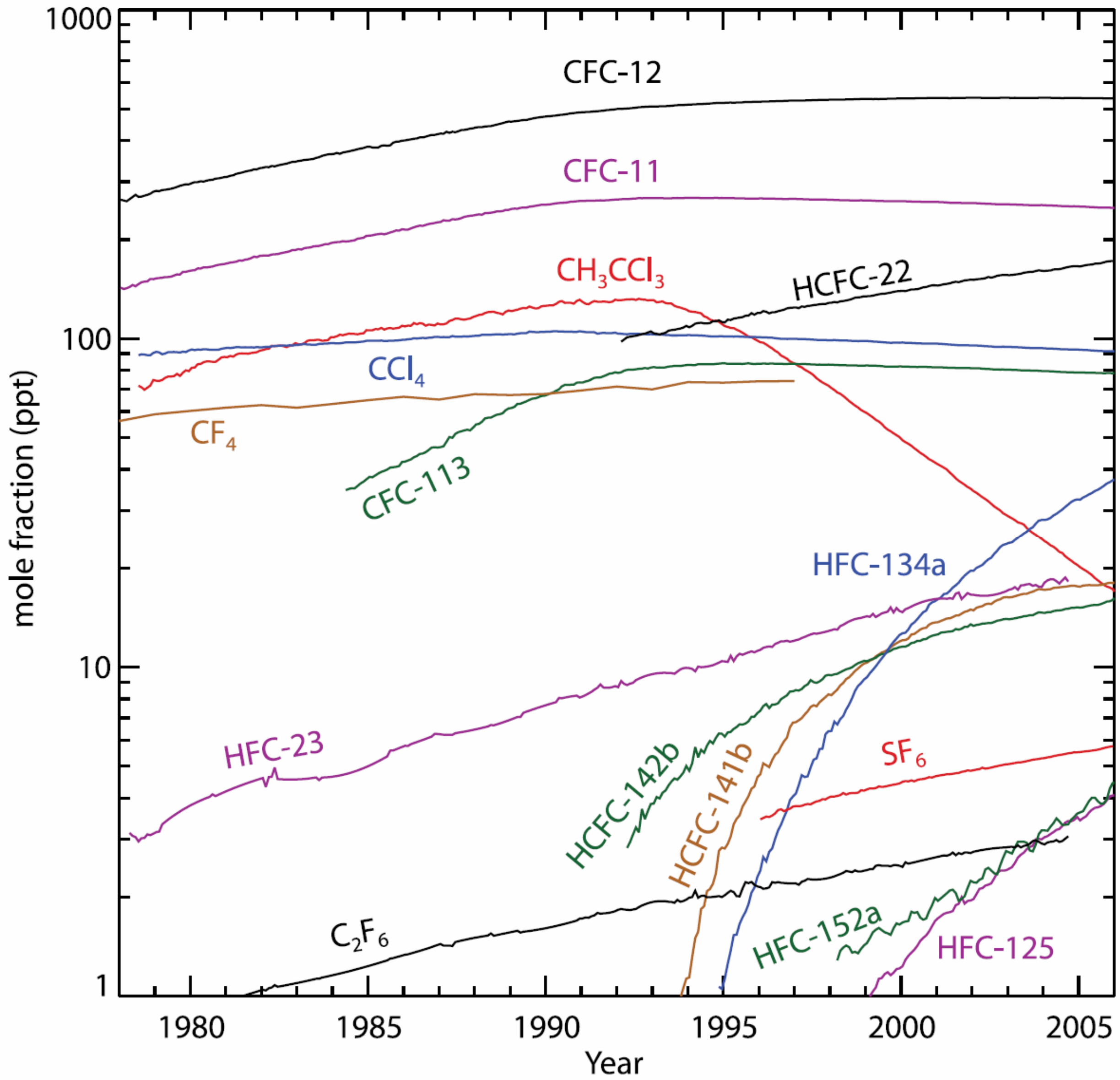
Source: Chapter 2, pg 141, Table 2.1. of the IPCC Fourth Assessment Report, 2007.

Atmospheric lifetime and GWP of various greenhouse gases relative to CO_2 at different time horizons

Name	**Chemical formula**	**Lifetime (years)**	**Global warming potential (GWP) for given time horizon**		
			20-yr	**100-yr**	**500-yr**
Carbon dioxide	CO_2	30-1000*	1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous Oxide	N_2O	114	289	298	153
CFC-12	CCl_2F_2	100	11 000	10 900	5 200
HCFC-22	$CHClF_2$	12	5 160	1 810	549
HCFC-134a	CF_3CH_2F	14		1430	
Tetrafluormethane	CF_4	50,000	5 210	7 390	11 200
Hexafluorethane	C_2F_6	10,000	8 630	12 200	18 200
Sulfur hexafluoride	SF_6	3,200	16 300	22 800	32 600
Nitrogen trifluoride	NF_3	740	12 300	17 200	20 700

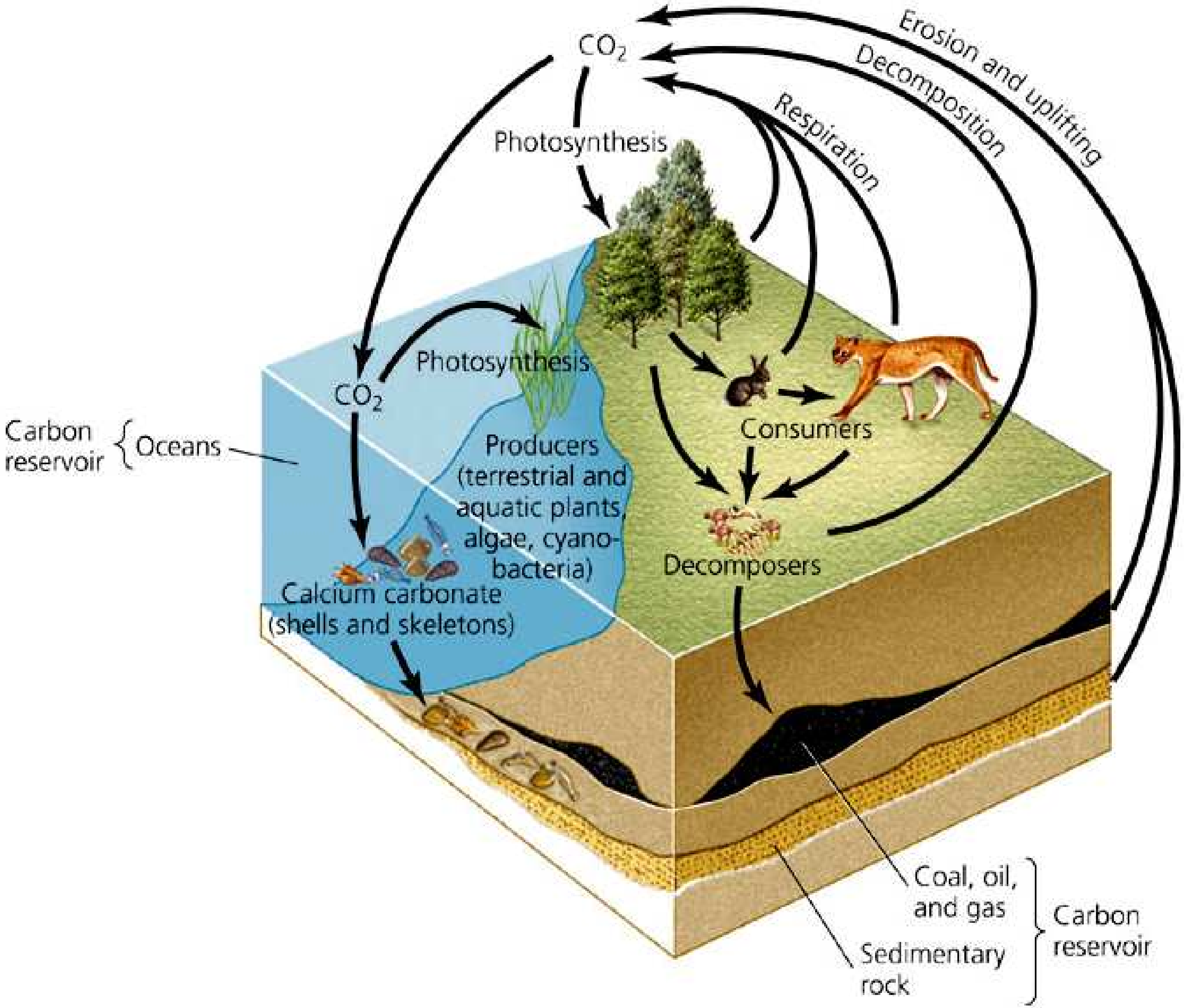
Source: Chapter 2, p. 145, Table 2.1 of the IPCC Fourth Assessment Report, 2007.

Temporal Evolution of Halogenated Greenhouse Gases

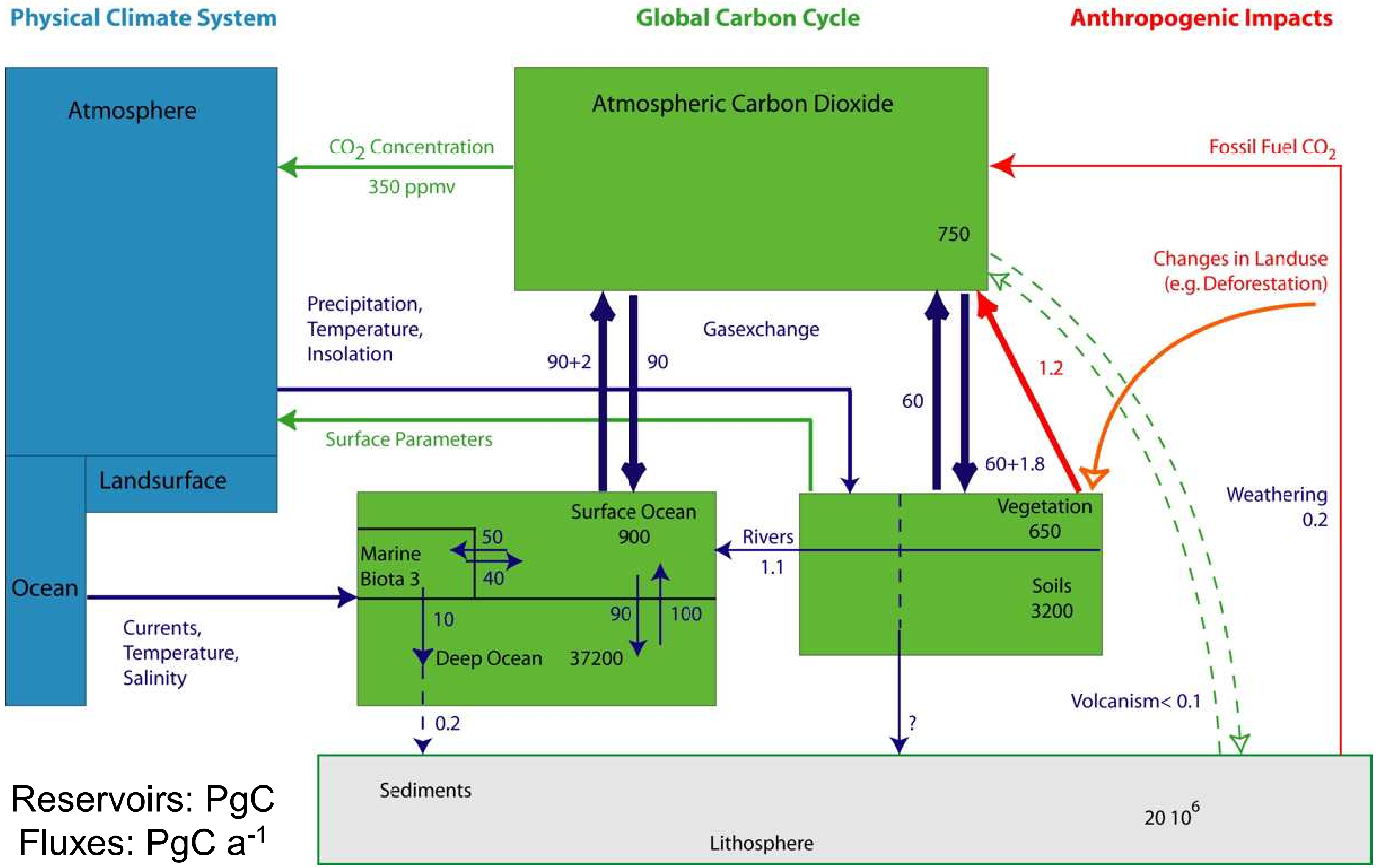


Source: Chapter 2, p. 145 of the IPCC Fourth Assessment Report, 2007.

The Global Carbon Cycle



The Global Carbon Cycle



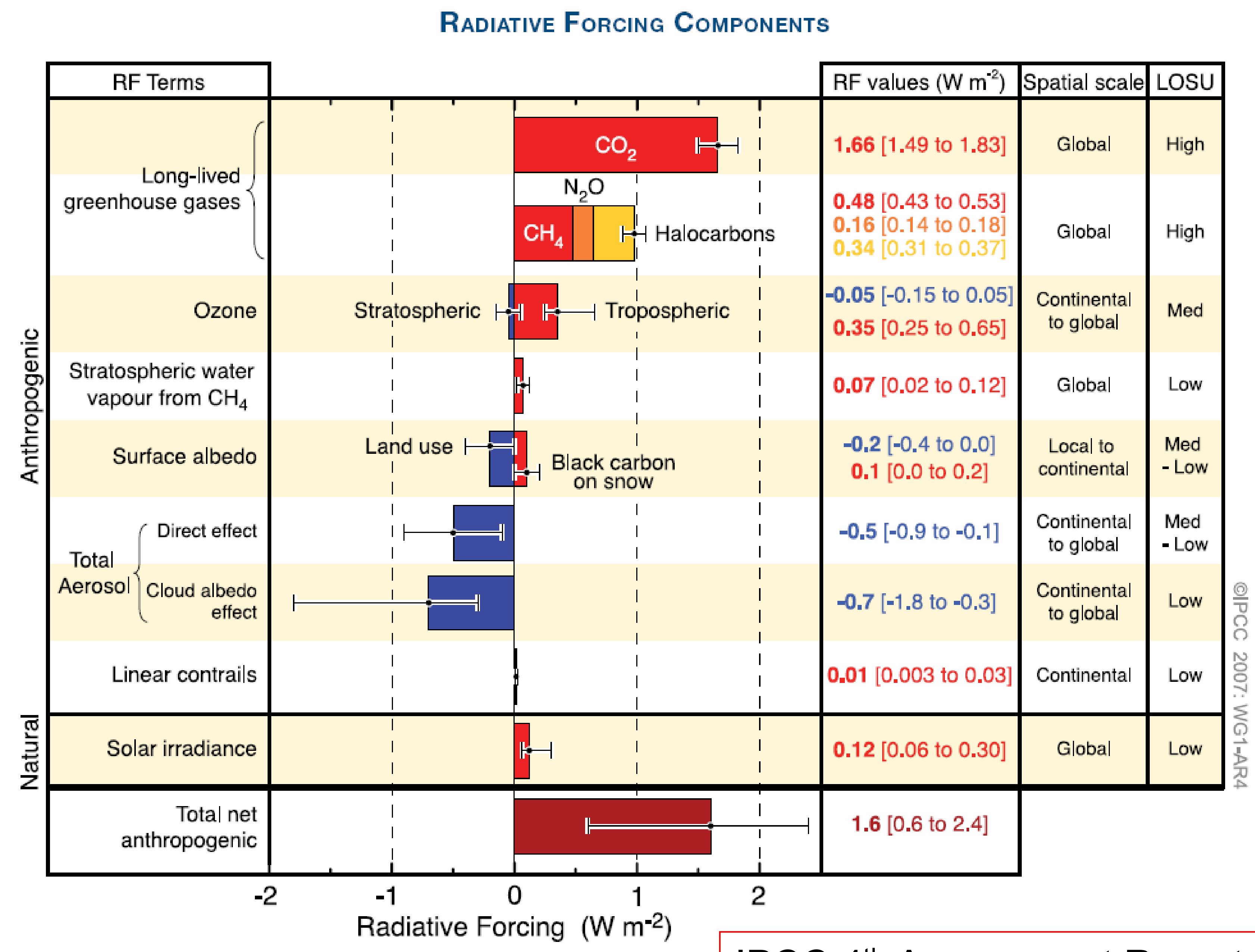
Reservoirs: PgC
Fluxes: PgC a^{-1}

Atmospheric Carbon Species

Species	mixing ratio	reservoir GtC	turnover GtC/a
CO_2	≈385 ppm	800	140
CH_4	≈1.7 ppm	3.3	0.3
CO	≈ 0.07-0.15 ppm	0.3	1.1
Non-methane hydrocarbons (NMHC)	<< to several ppb	0.03	0.3-0.8

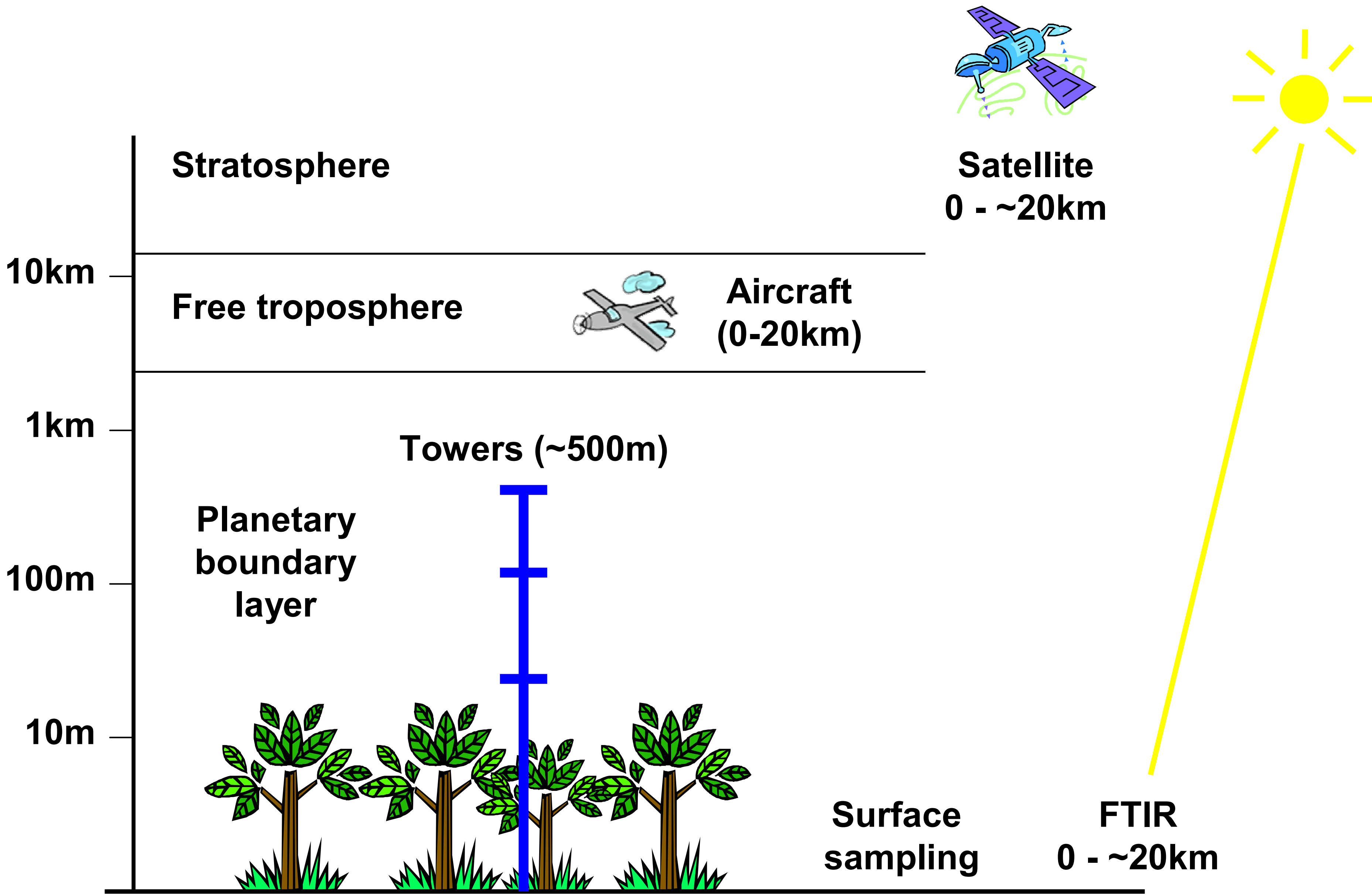
Reservoir size: GtC or 10^9t or 10^{15}g or peta-gramm

Why are we interested in Atmospheric Carbon Species?



IPCC 4th Assessment Report, 2007

Measurements of Atmospheric CO_2



First Detection of Systematic Atmospheric CO_2 Variations

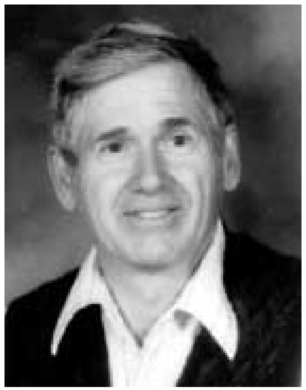
The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere

By CHARLES D. KEELING, Scripps Institution of Oceanography, University of California, La Jolla, California

(Manuscript received March 25, 1960)

Abstract

A systematic variation with season and latitude in the concentration and isotopic abundance of atmospheric carbon dioxide has been found in the northern hemisphere. In Antarctica, however, a small but persistent increase in concentration has been found. Possible causes for these variations are discussed.



Charles David Keeling
(1928-2005)

C. D. Keeling, Tellus, v12, 200, 1960

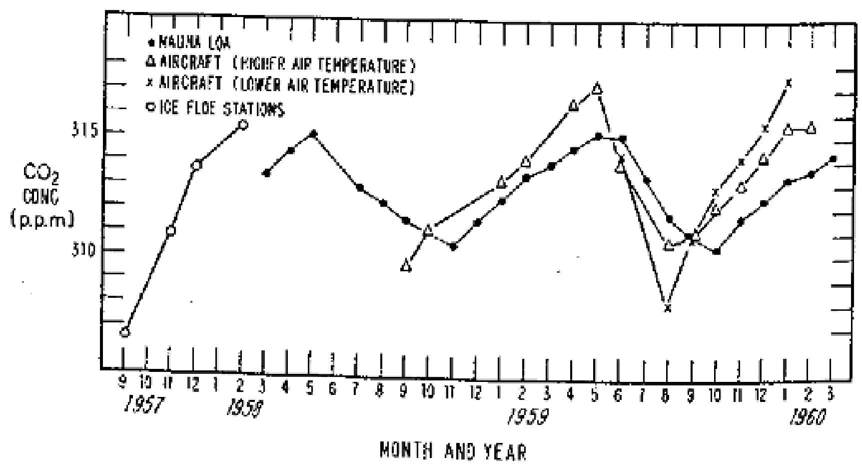
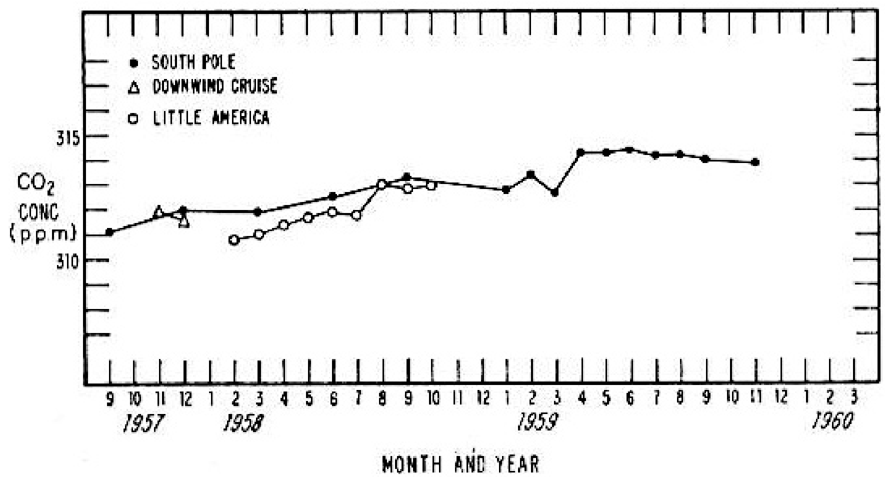
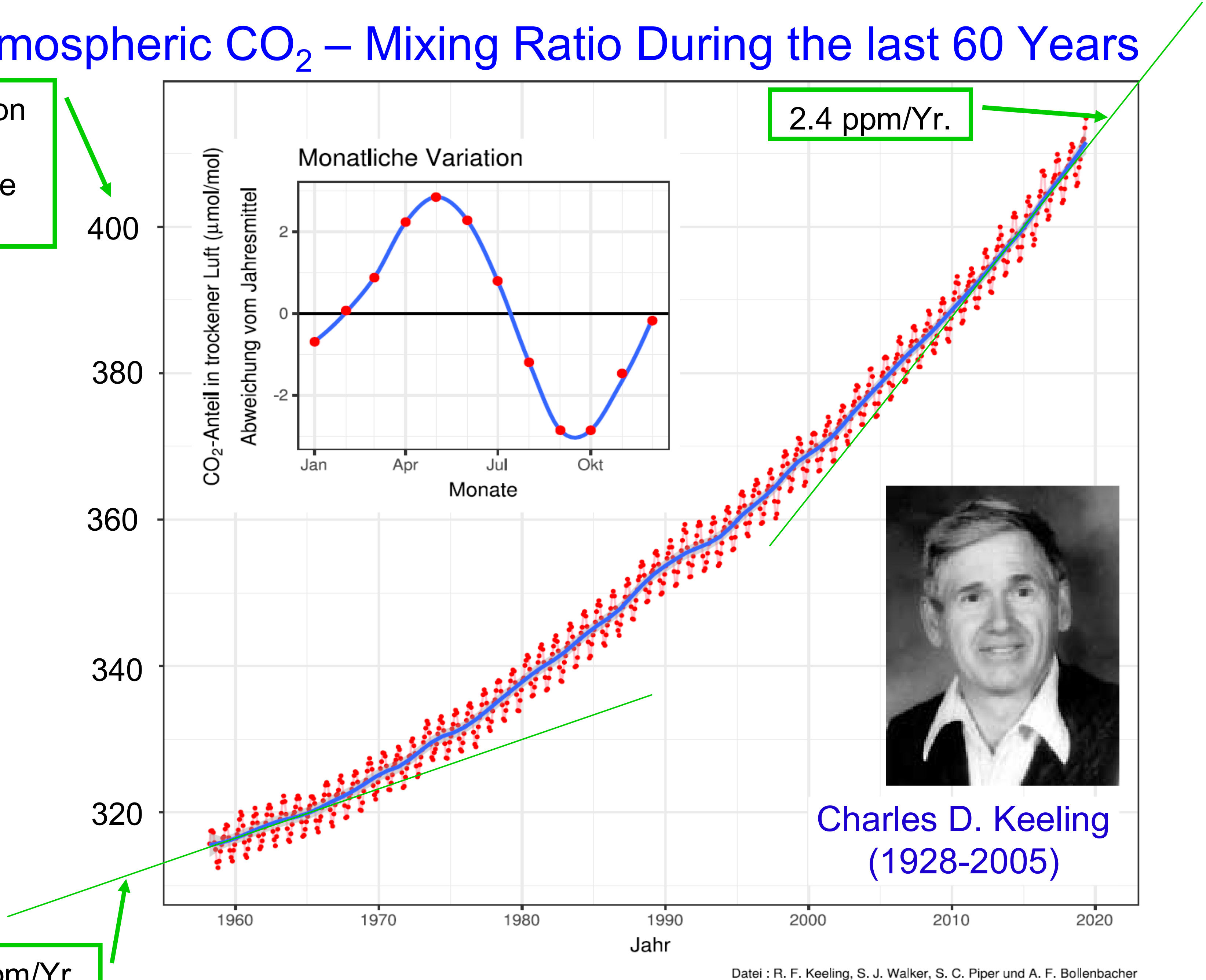


Fig. 1. Variation in concentration of atmospheric carbon dioxide in the Northern Hemisphere.

Tellus XII (1960), 2



The Atmospheric CO_2 – Mixing Ratio During the last 60 Years

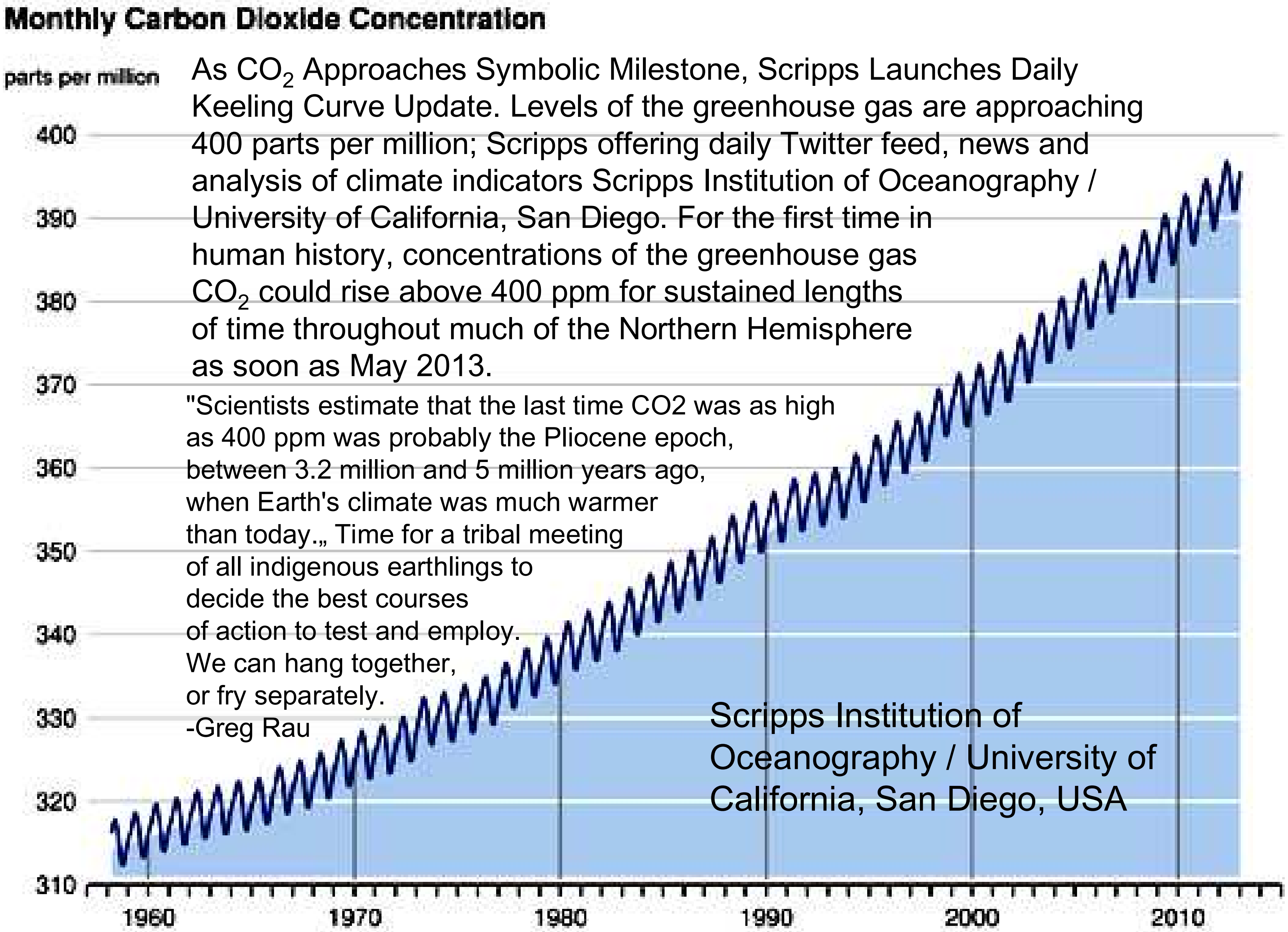


Charles D. Keeling
(1928-2005)

Scripps

Mauna Loa, Hawaii, USA, 3397m a.s.l.

CO_2 Levels 1957 - 2013

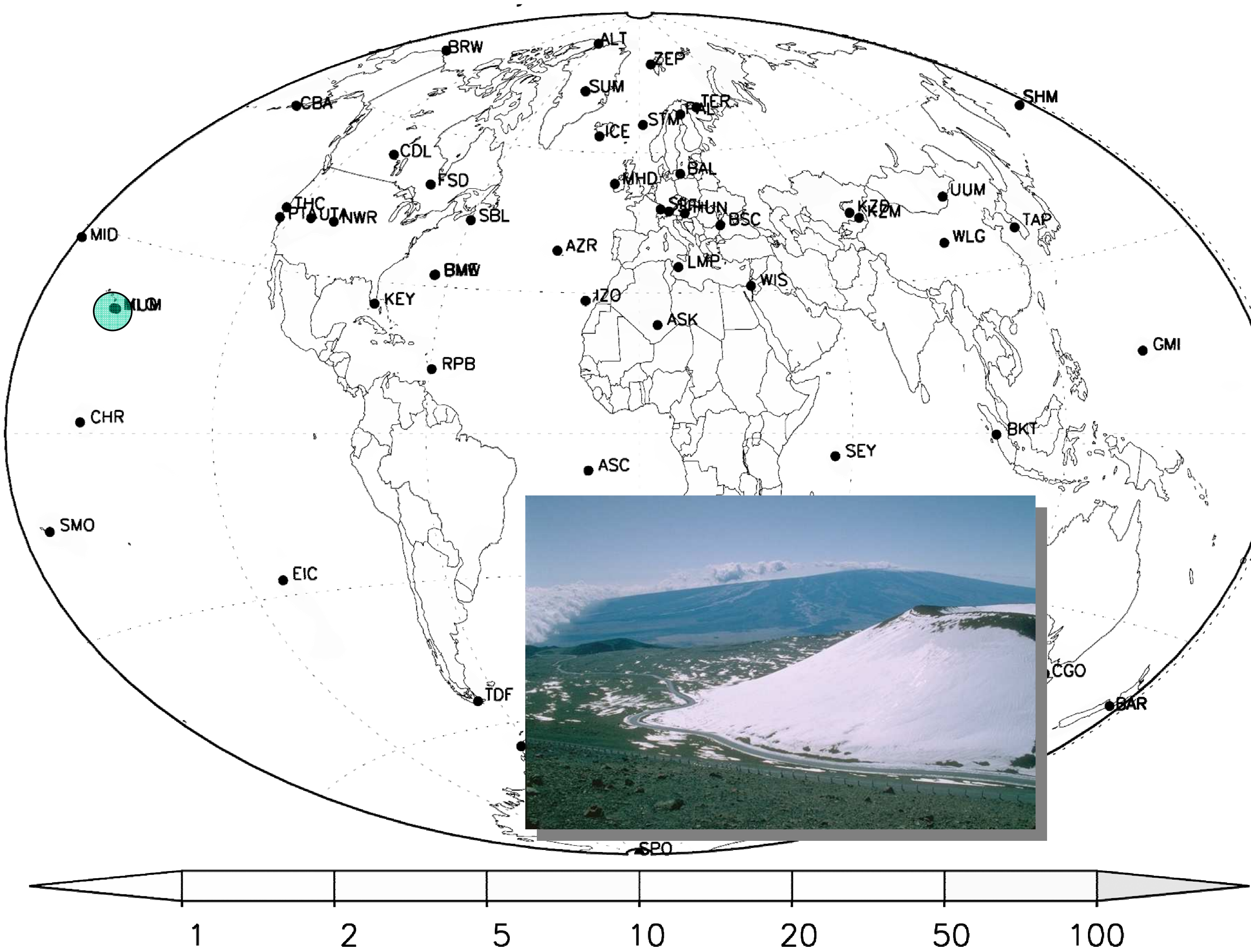


As CO_2 Approaches Symbolic Milestone, Scripps Launches Daily Keeling Curve Update. Levels of the greenhouse gas are approaching 400 parts per million; Scripps offering daily Twitter feed, news and analysis of climate indicators Scripps Institution of Oceanography / University of California, San Diego. For the first time in human history, concentrations of the greenhouse gas CO_2 could rise above 400 ppm for sustained lengths of time throughout much of the Northern Hemisphere as soon as May 2013.

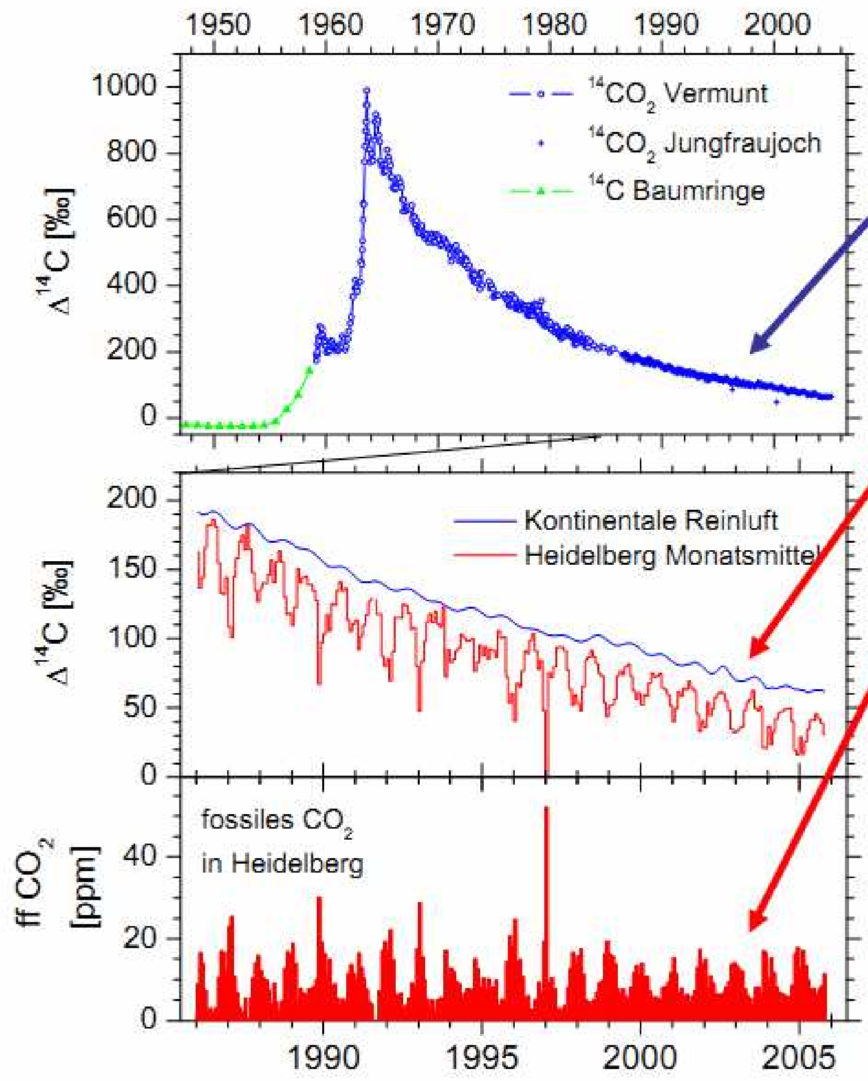
"Scientists estimate that the last time CO2 was as high as 400 ppm was probably the Pliocene epoch, between 3.2 million and 5 million years ago, when Earth's climate was much warmer than today.„ Time for a tribal meeting of all indigenous earthlings to decide the best courses of action to test and employ. We can hang together, or fry separately.
-Greg Rau

Scripps Institution of Oceanography / University of California, San Diego, USA

Ground-Based Network for Atmospheric CO_2 Monitoring



Long-Term CO_2 and ^{14}C – Measurements in Heidelberg



Levin et al.

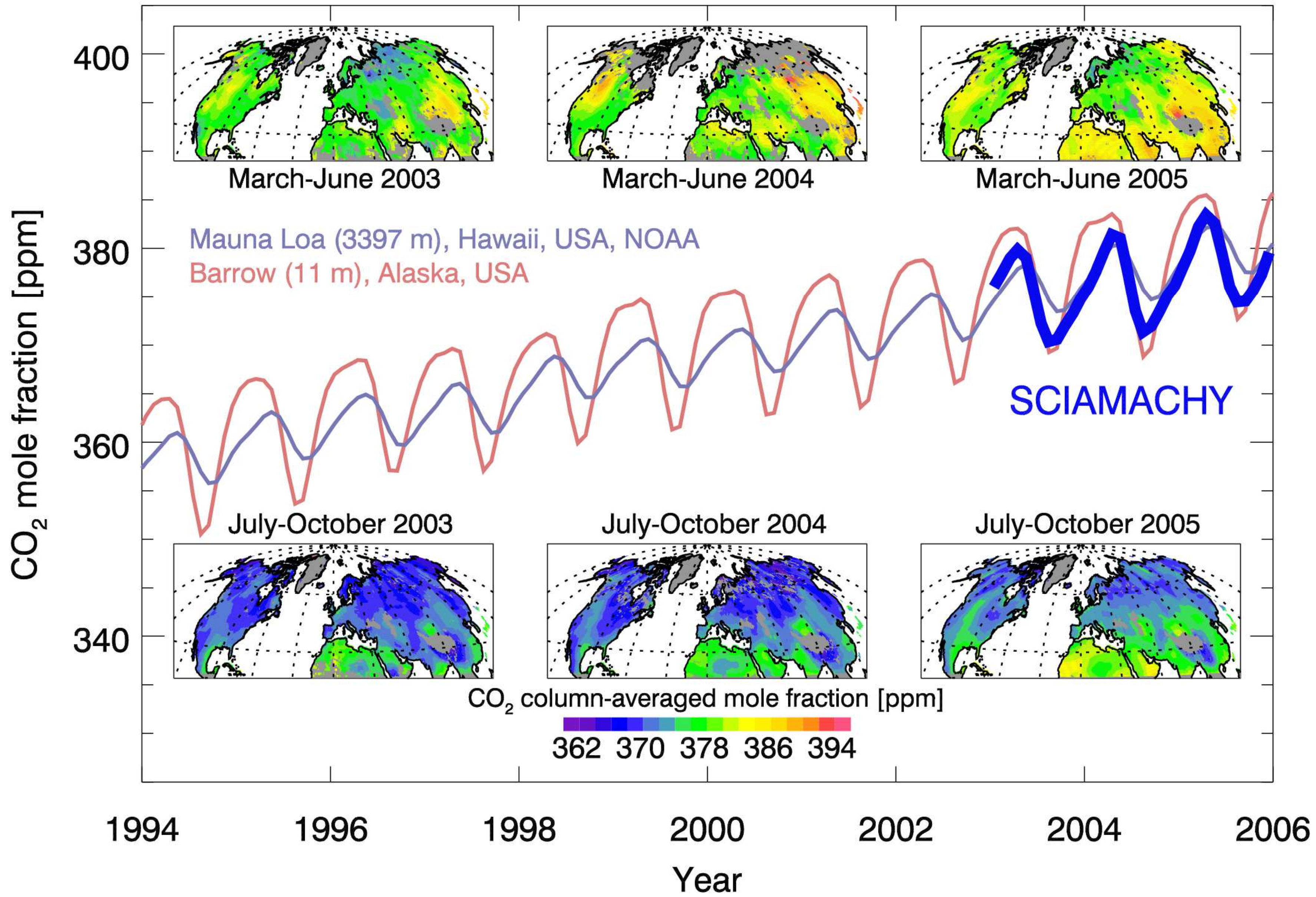
Clean air $\Delta^{14}CO_2$ –Level in the Alps

$\Delta^{14}CO_2$-depression due to fossil CO_2

fossil CO_2-mixing ratio

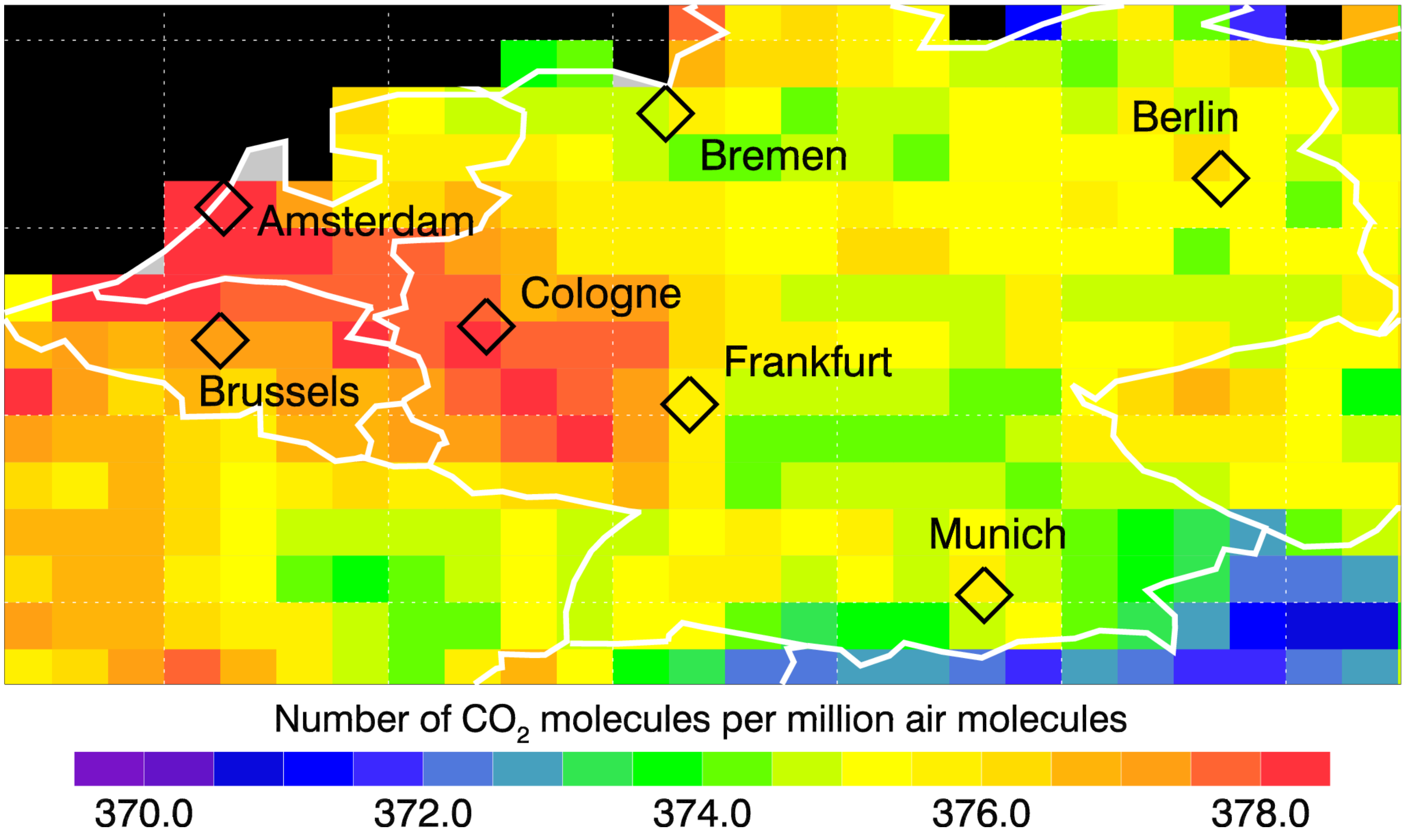
Levin et al. (2008), Radiocarbon observations in atmospheric CO_2: Determining fossil fuel CO_2 over Europe using Jungfraujoch observations as background, Science of The Total Environment, 391 (2–3), 211-216

Satellite Measurements of CO_2 (Northern Hemisphere)



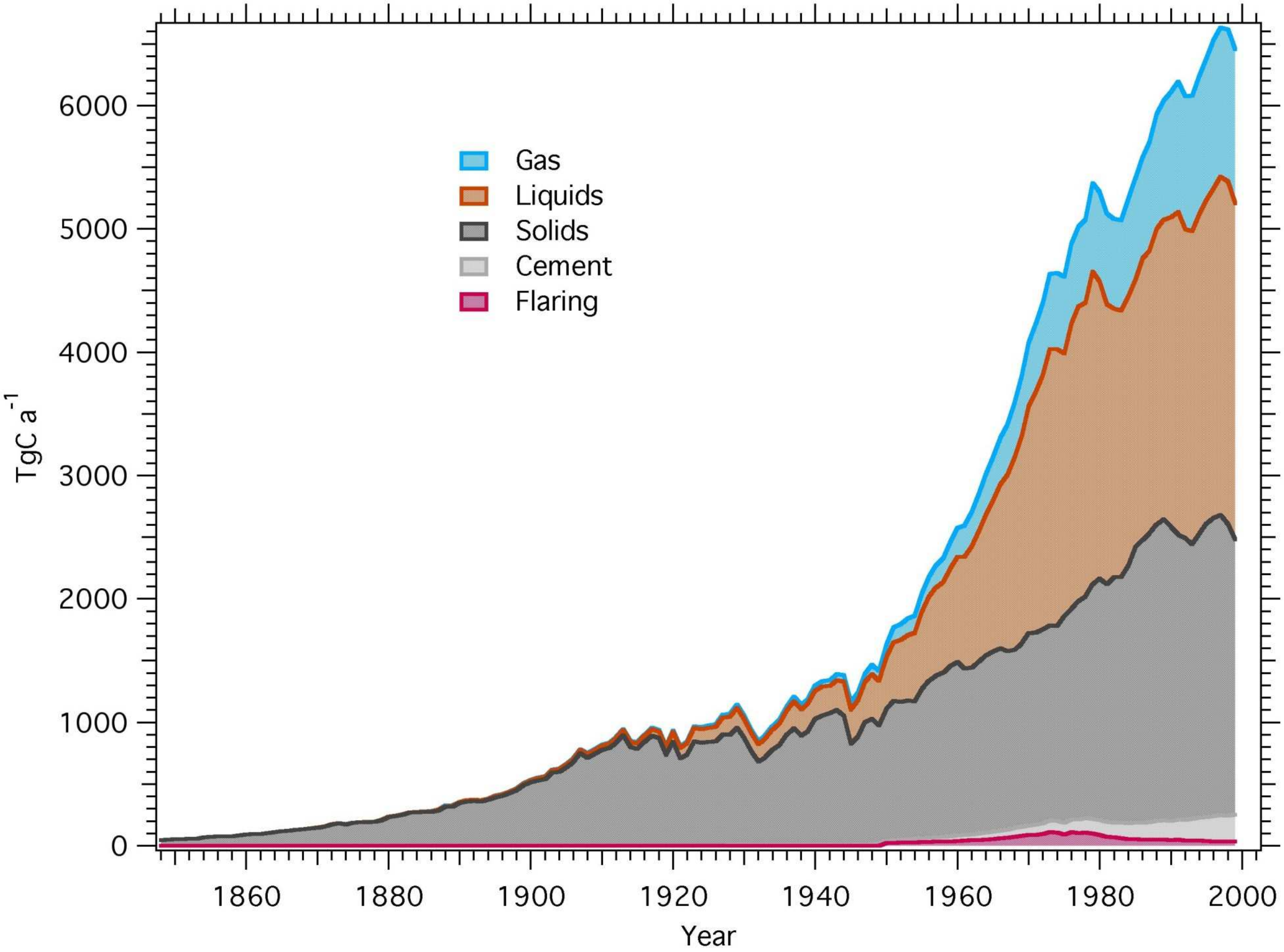
Institute for Environmental Physics, University of Bremen

Mean CO_2 from SCIAMACHY 2003-2005

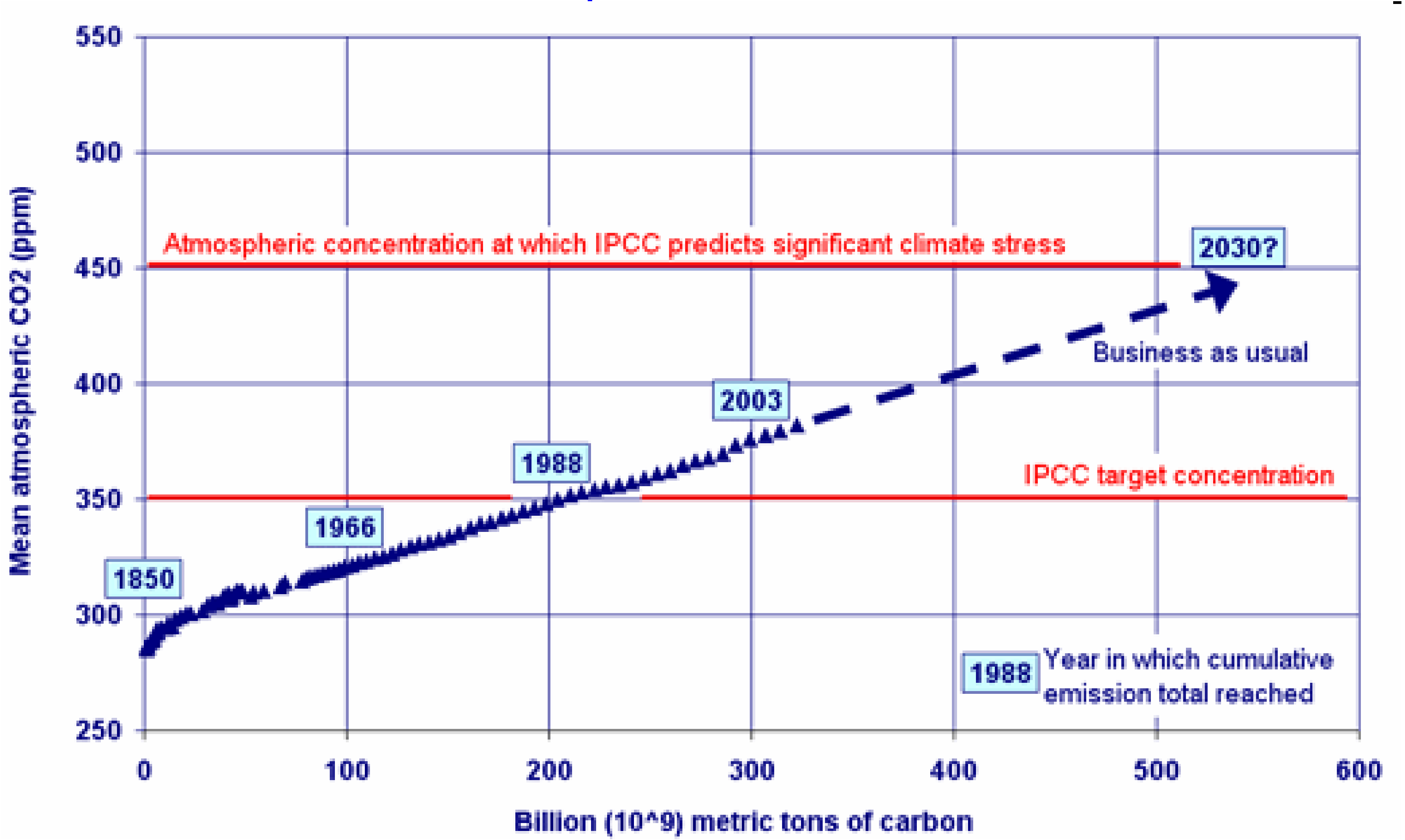


Institute for Environmental Physics, University of Bremen

Anthropogenic CO_2 Emissions (as Carbon) since 1850

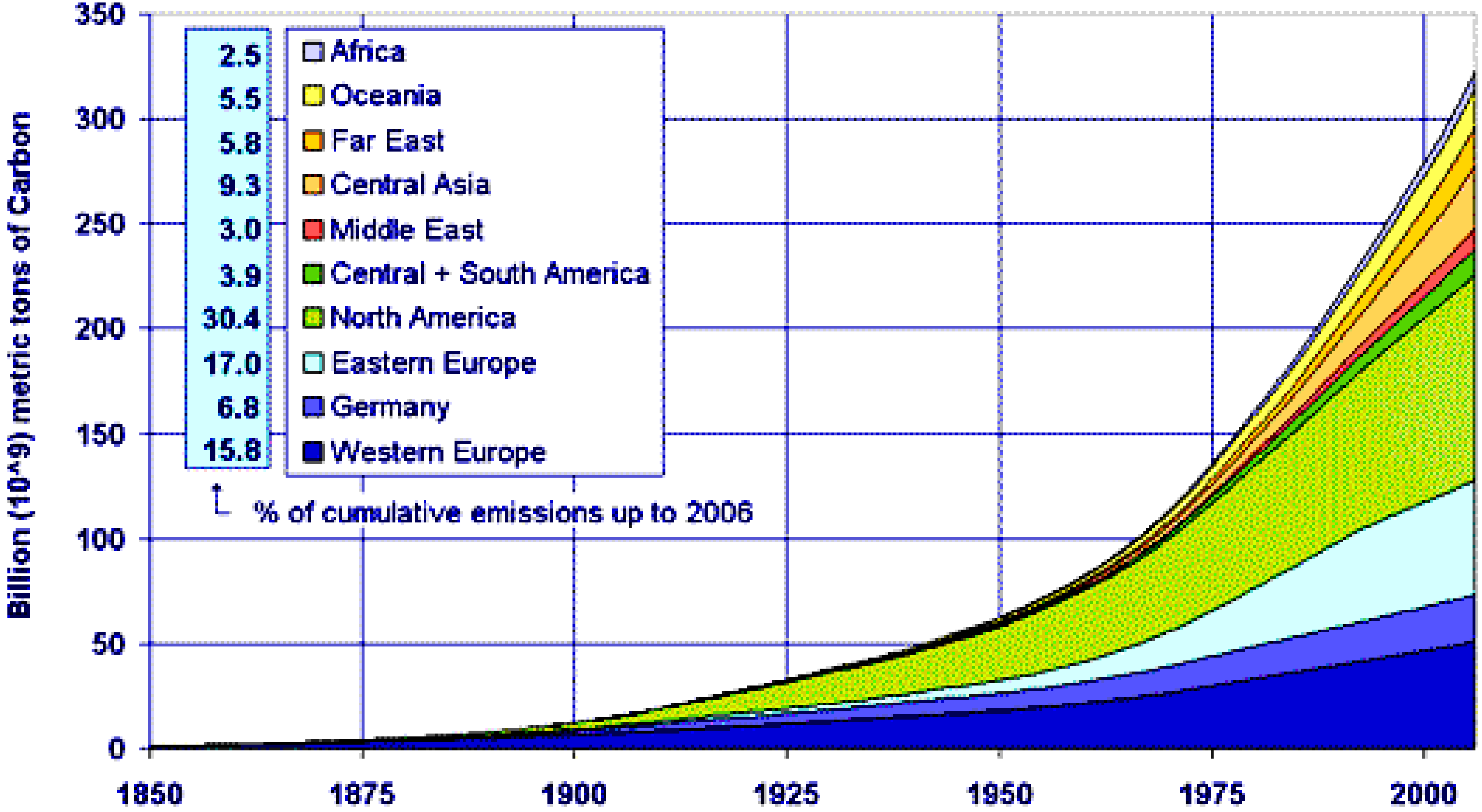


Cumulative Anthropogenic Emissions of Carbon Dioxide to the Atmosphere since 1850



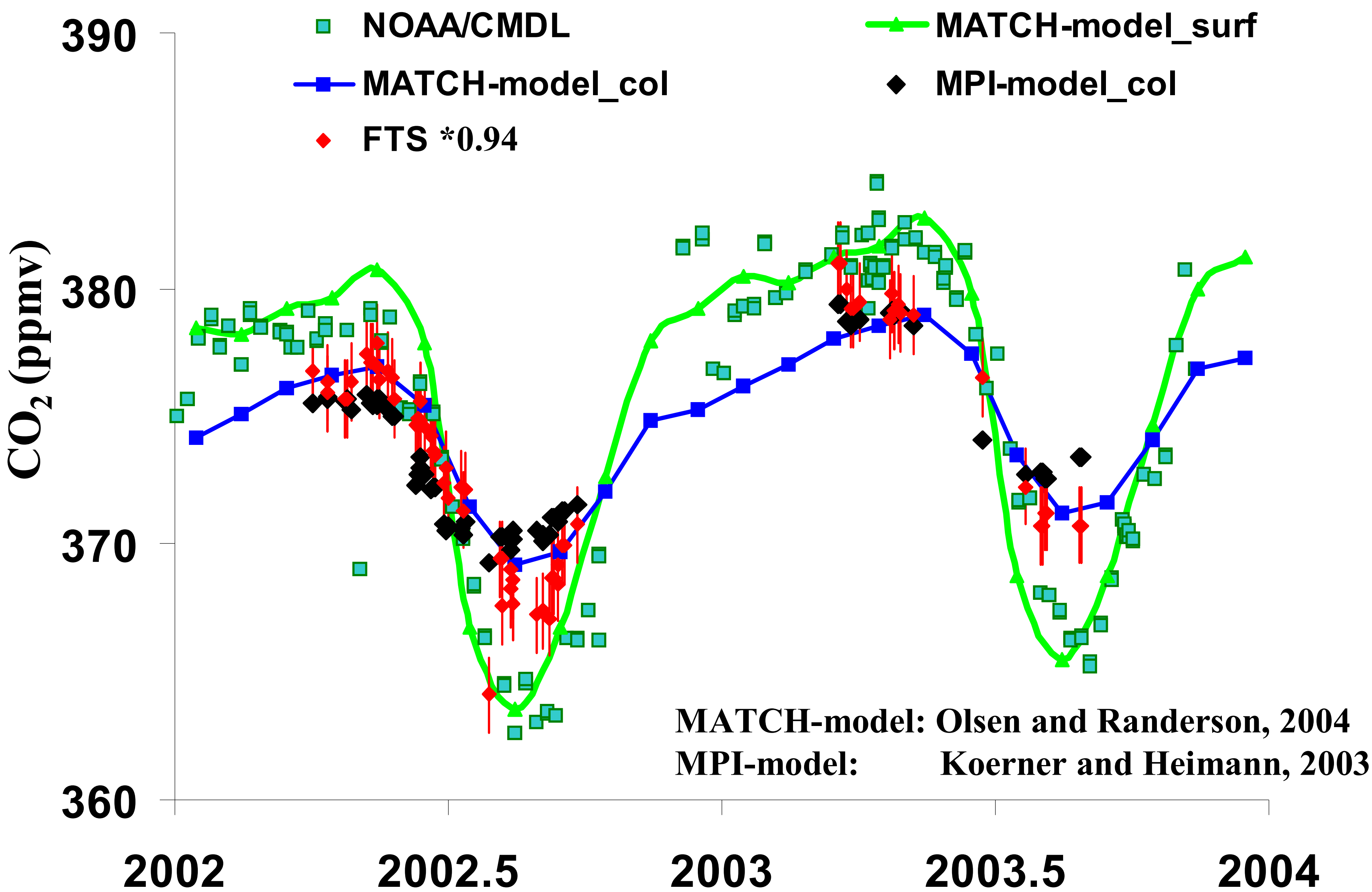
Source of data: Carbon Dioxide Information Analysis Center (CDIAC.com) and values of atmospheric CO_2 concentrations from Mauna Loa, as well as other locations. Excluding carbon emissions from change of land use and deforestation.

Cumulative Anthropogenic Emissions of Carbon to the Atmosphere since 1850-2006



Source of data: Carbon Dioxide Information Analysis Center (CDIAC.com) and values of atmospheric CO2 concentrations from Mauna Loa, as well as other locations. Excluding carbon emissions from change of land use and deforestation.

Seasonal variation of CO_2 at Ny Alesund



Seasonal and latitudinal variation of CO_2 at the surface

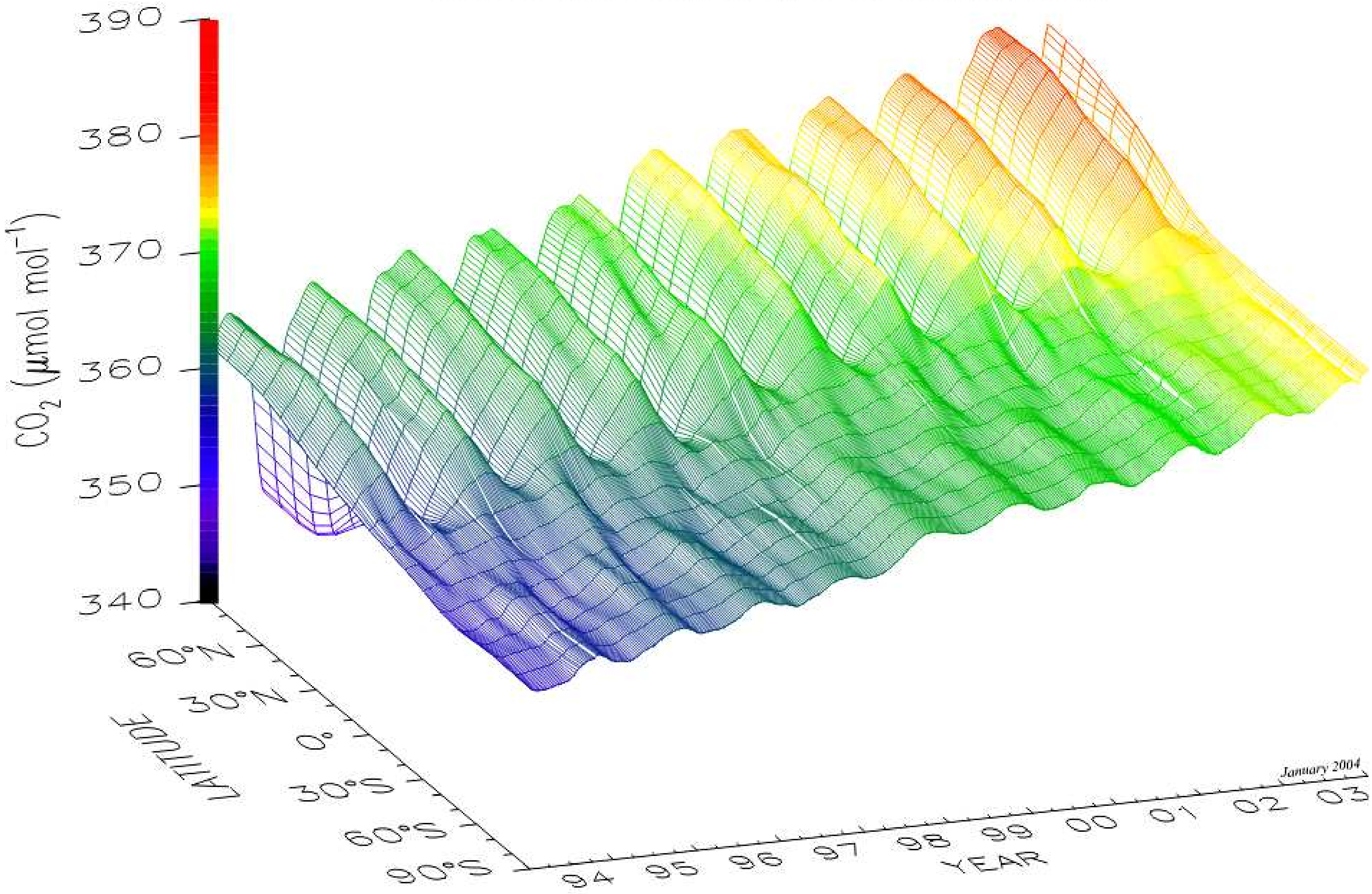
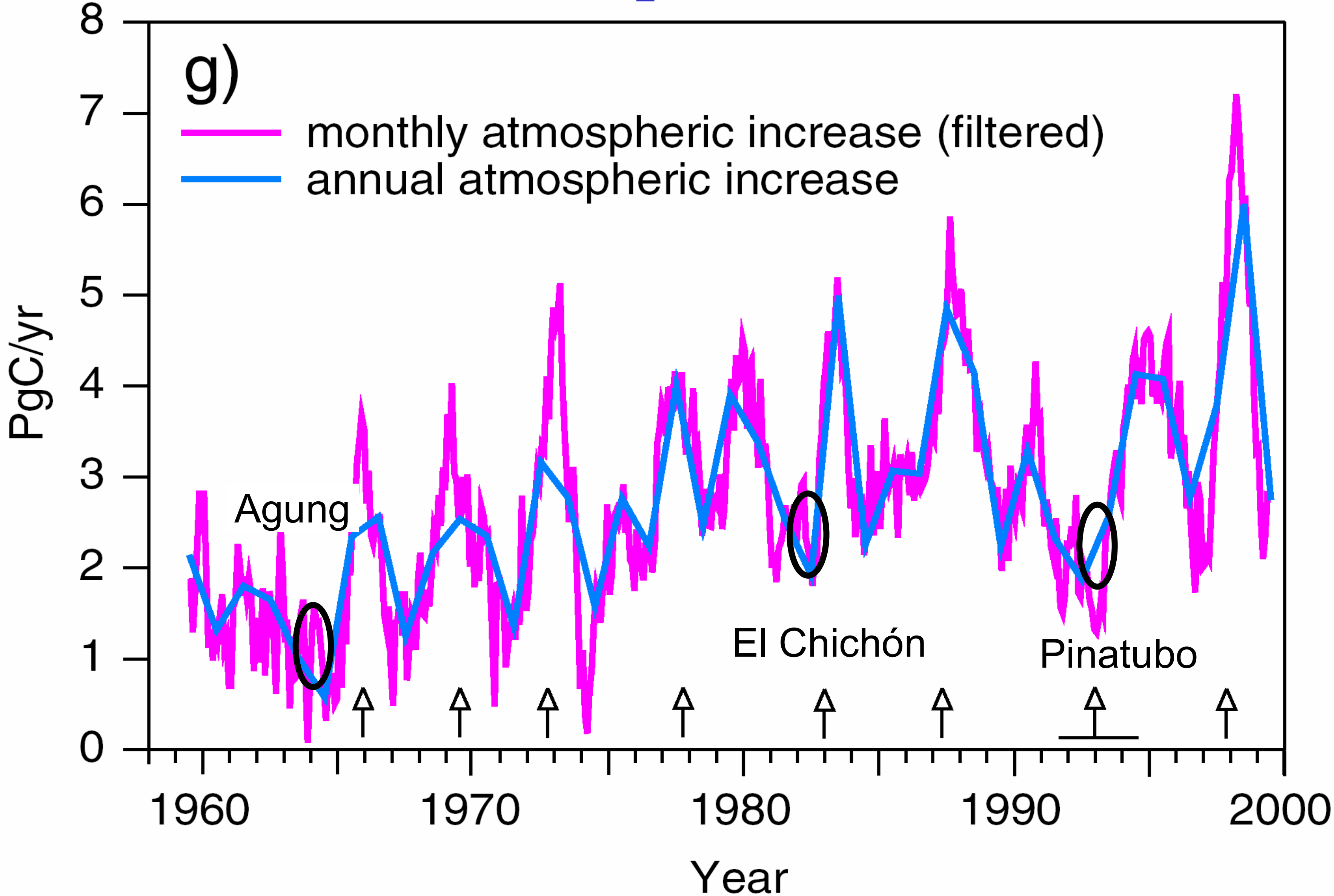


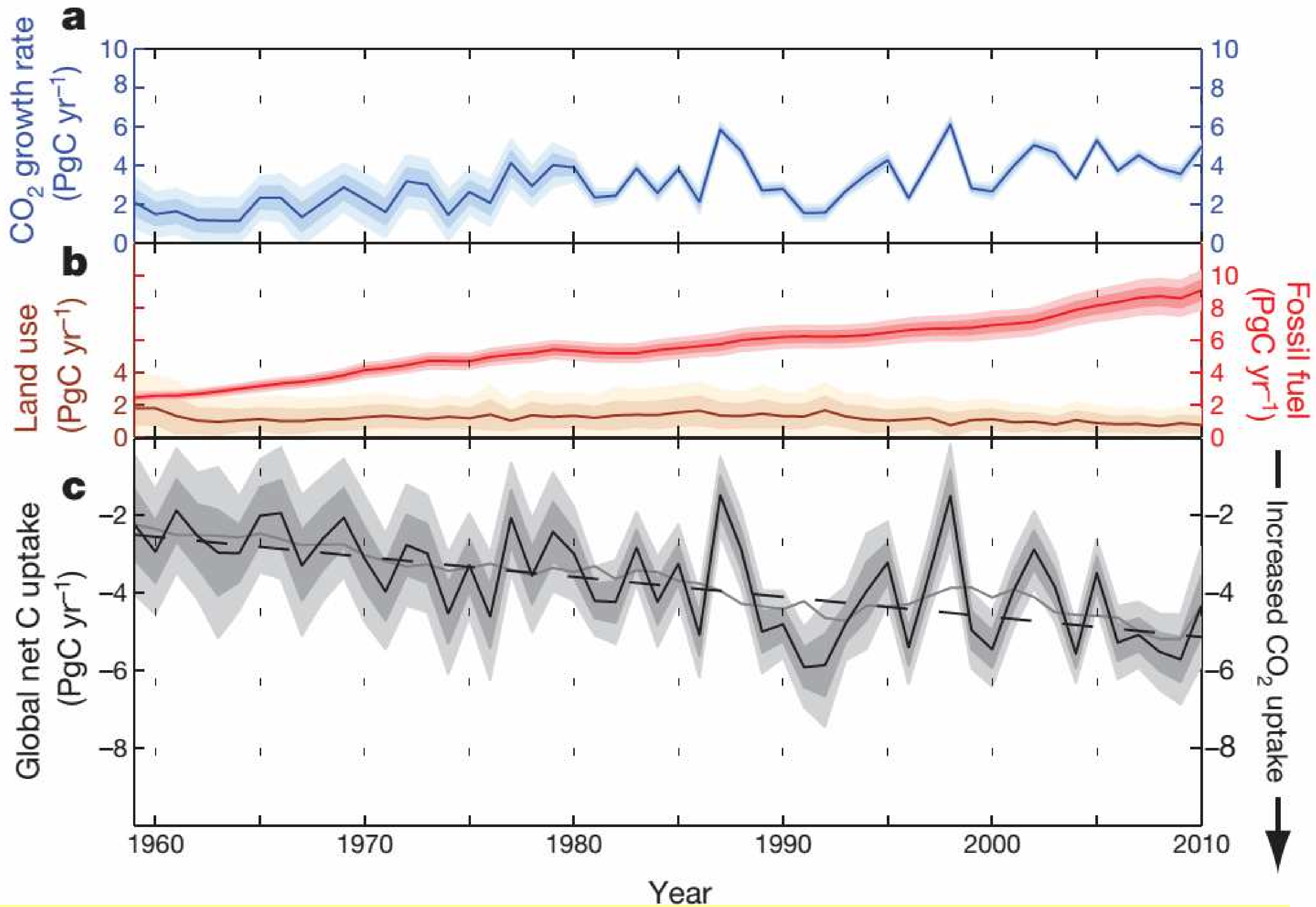
Fig. from NOAA/CMDL

Atmospheric CO_2 - Rate of Increase



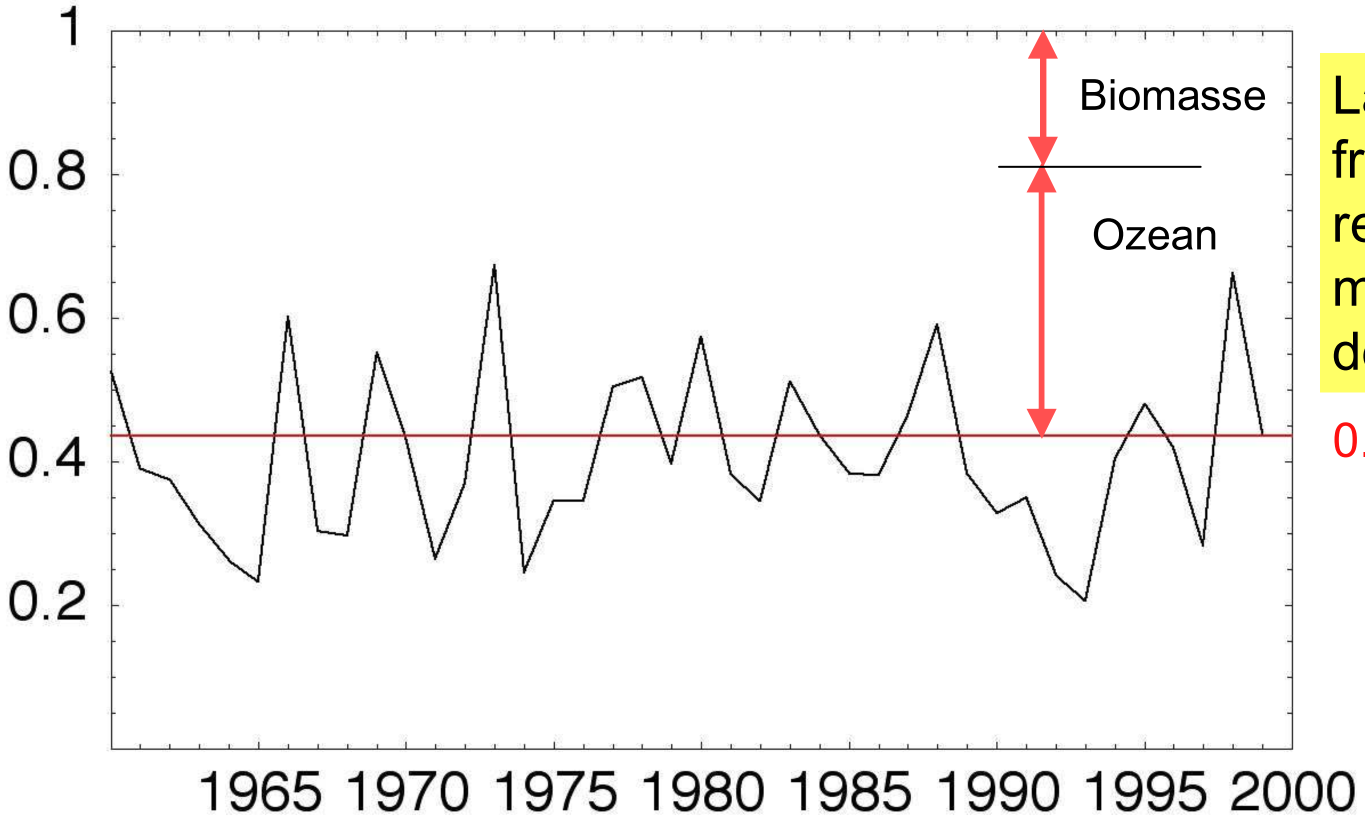
- **atmospheric increase ~44% of fossil fuel emissions**
- **large interannual variability**

CO_2 Growth-Rate and Uptake



Ballantyne A.P., Alden C.B., Miller J.B., Tans P.P.& White J.W.C. (2012), Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years, Nature 488, 70-72.

The "Airborne Fraction" of the emitted CO_2, $A_F = n_a / Q_{tot}$

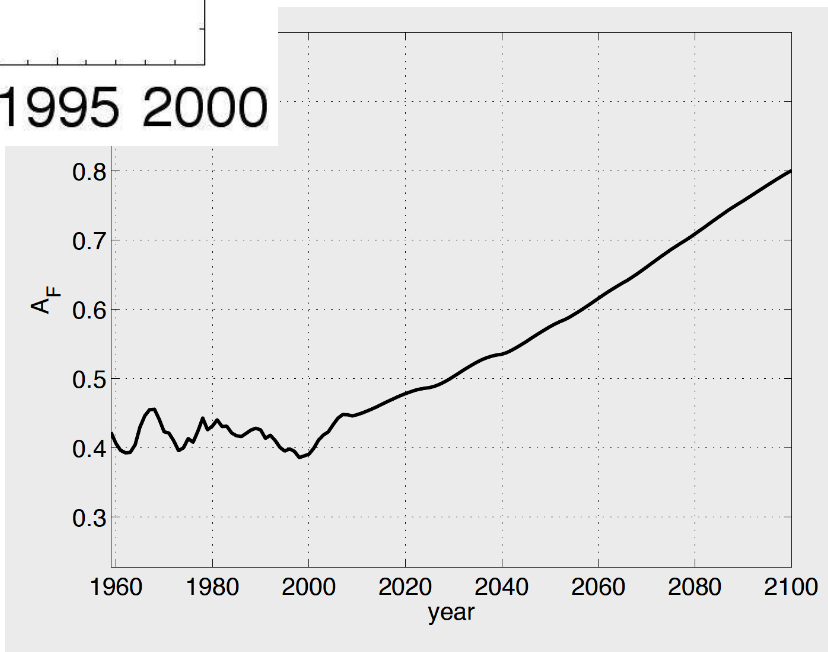


Large variations of A_F from year to year but remarkably constant mean during recent decades

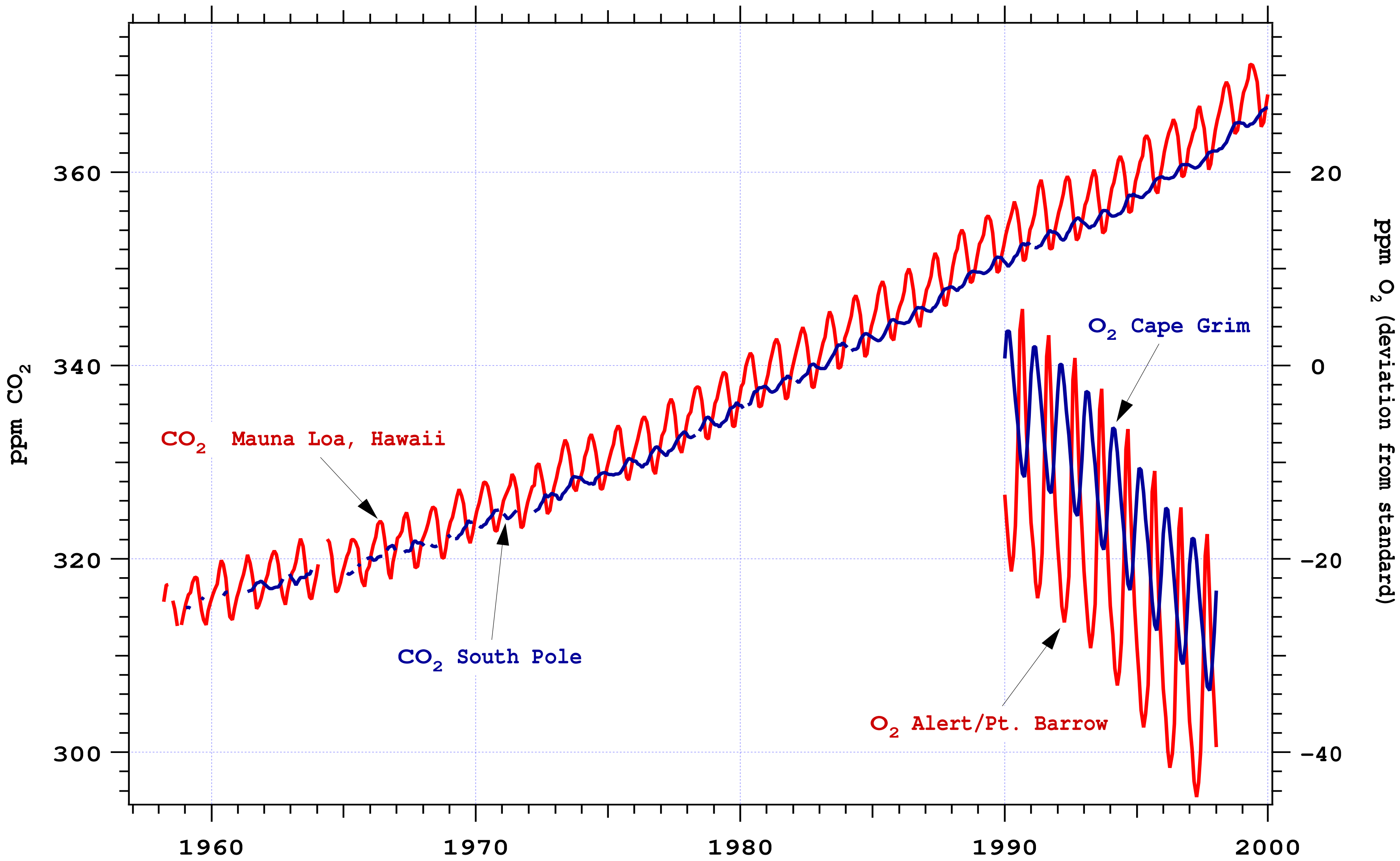
0.44

Model prediction of A_F:

Terenzi and Khatiwala, Tellus 2009



The Recent History of Atmospheric CO_2 and O_2 in the Atmosphere



Observations: Keeling & Keeling, SIO

Atmospheric Trends of CO_2 und O_2 "IPCC-Budget" (1990-2000)

Time	CO_2	O_2 (rel.)
1990:	357ppm	-17ppm
2000:	367ppm	-57ppm

ΔCO_2 +10 ppm

ΔO_2 - 40 ppm

Corresponds to
ΔCO_2: +25ppm

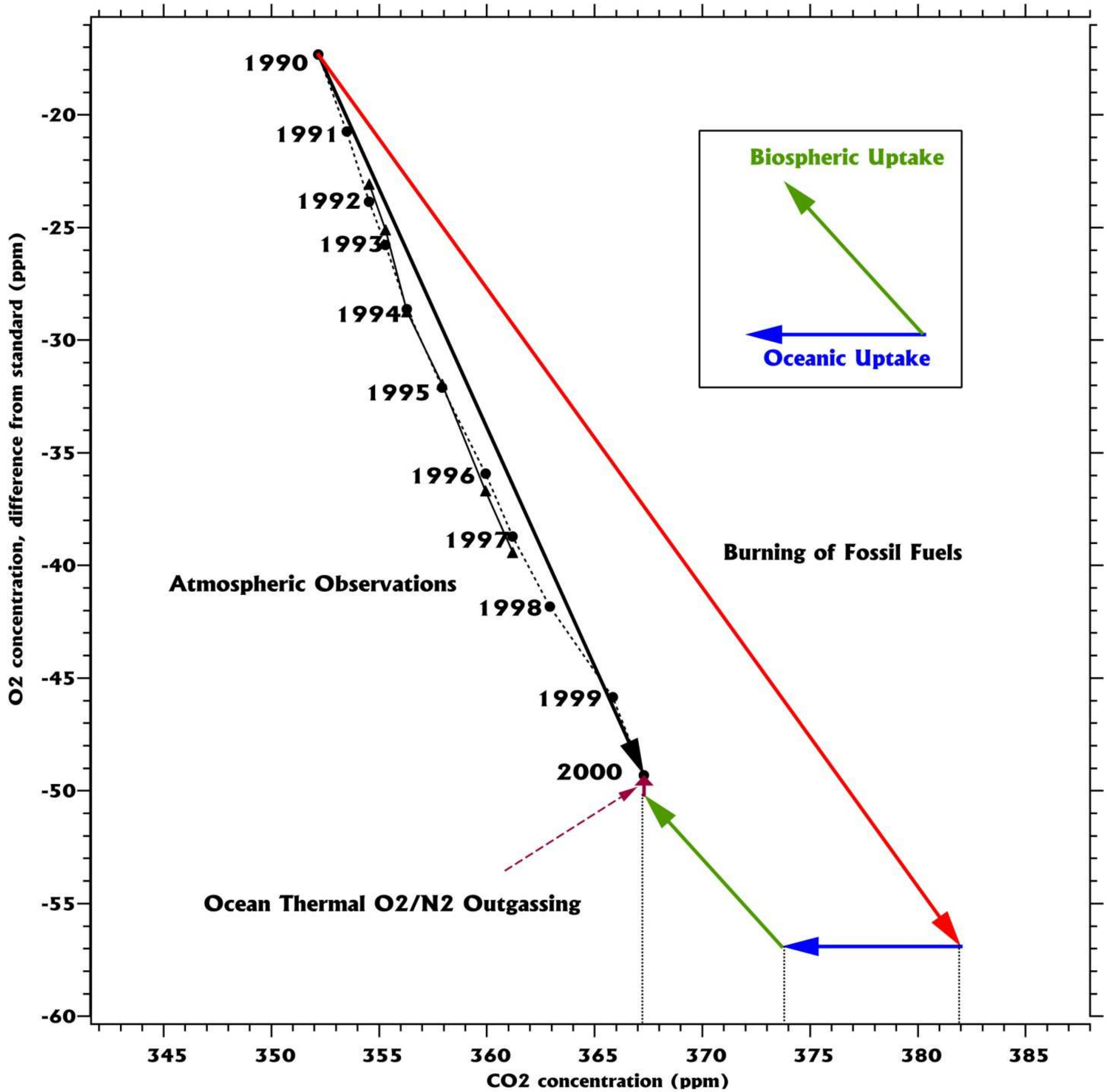
(combustion of oil and gas)

Ocean uptake:
no release of O_2

Photosynthesis:

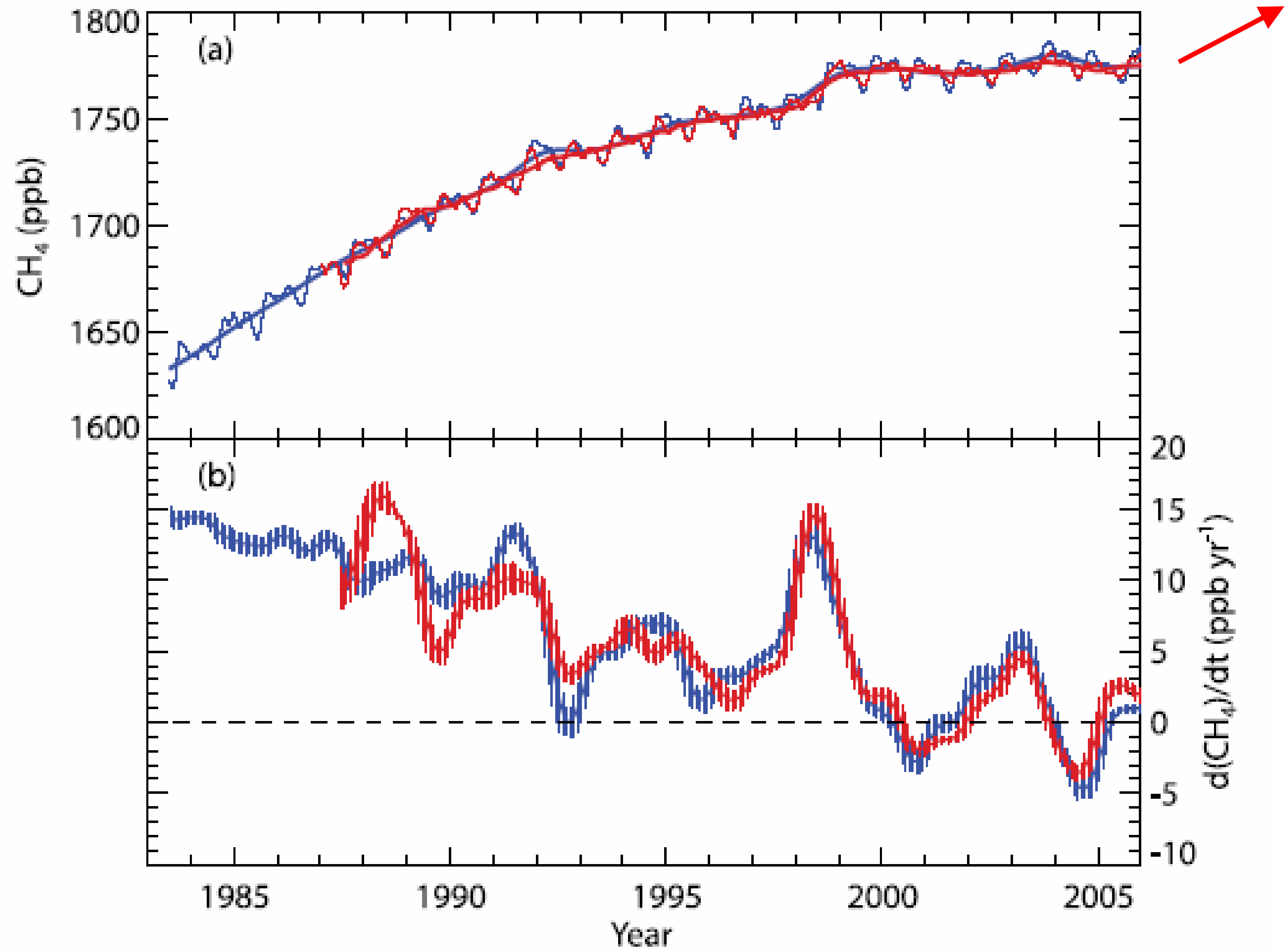
$CO_2 + H_2O \rightarrow CH_2O + O_2$

→ one O_2 per CO_2



Observations: Manning and Keeling, SIO, Battle et al., URI

The Atmospheric CH_4 Mixing Ratio and Growth Rate



IPCC 4th Assessment Report, 2007

The Oceanic Carbon Cycle

Three Transport Mechanisms:

- Advection and mixing through ocean currents (“Solubility Pump”)

Marine biological “pumps”:
- Organic carbon
- Carbonates

DIC = $H_2CO_3 + HCO_3^- + CO_3^{=}$
= Dissolved Inorganic Carbon

DIC equations:

$F_{as} = k_{ex}\,(pCO_{2,atm} - pCO_{2,oc})$

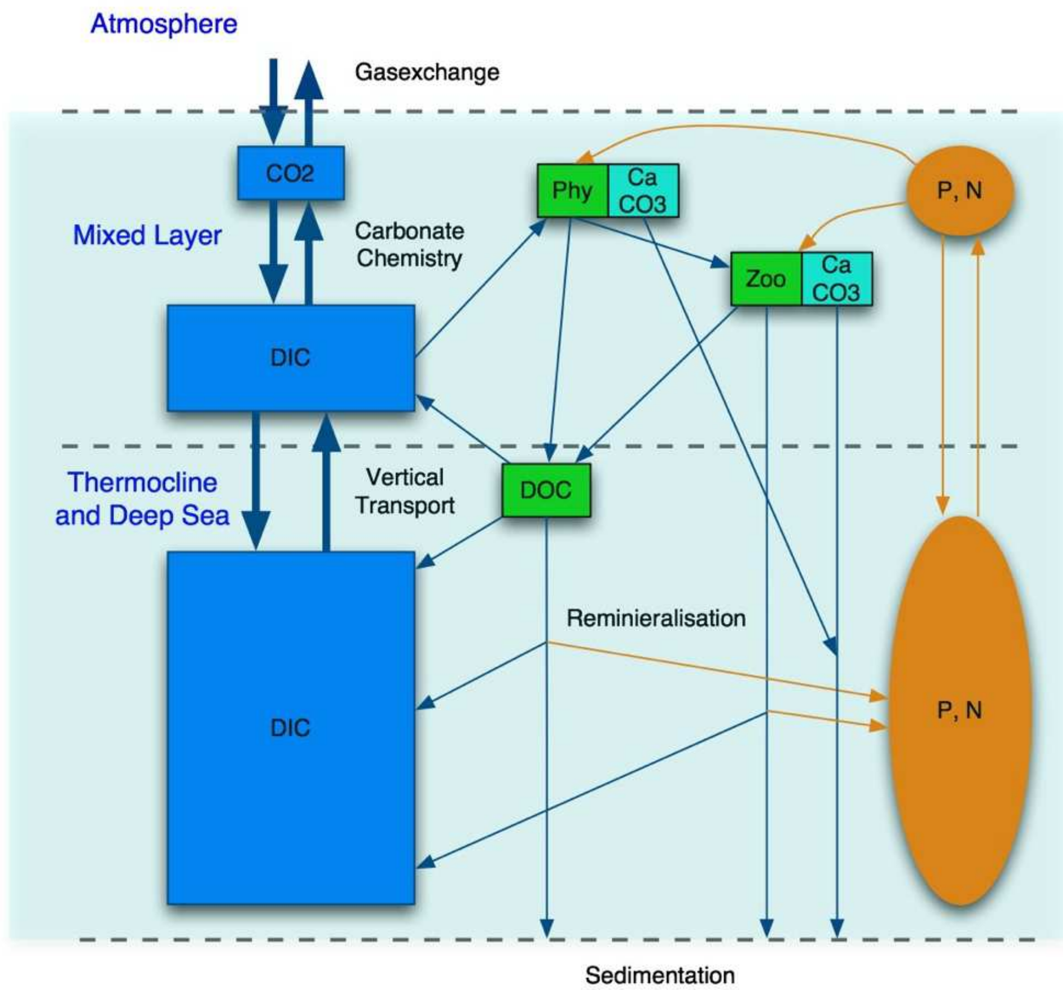
$pCO_{2,oc} = \alpha\,[H_2CO_3]$

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$

$HCO_3^- \leftrightarrow H^+ + CO_3^{=}$

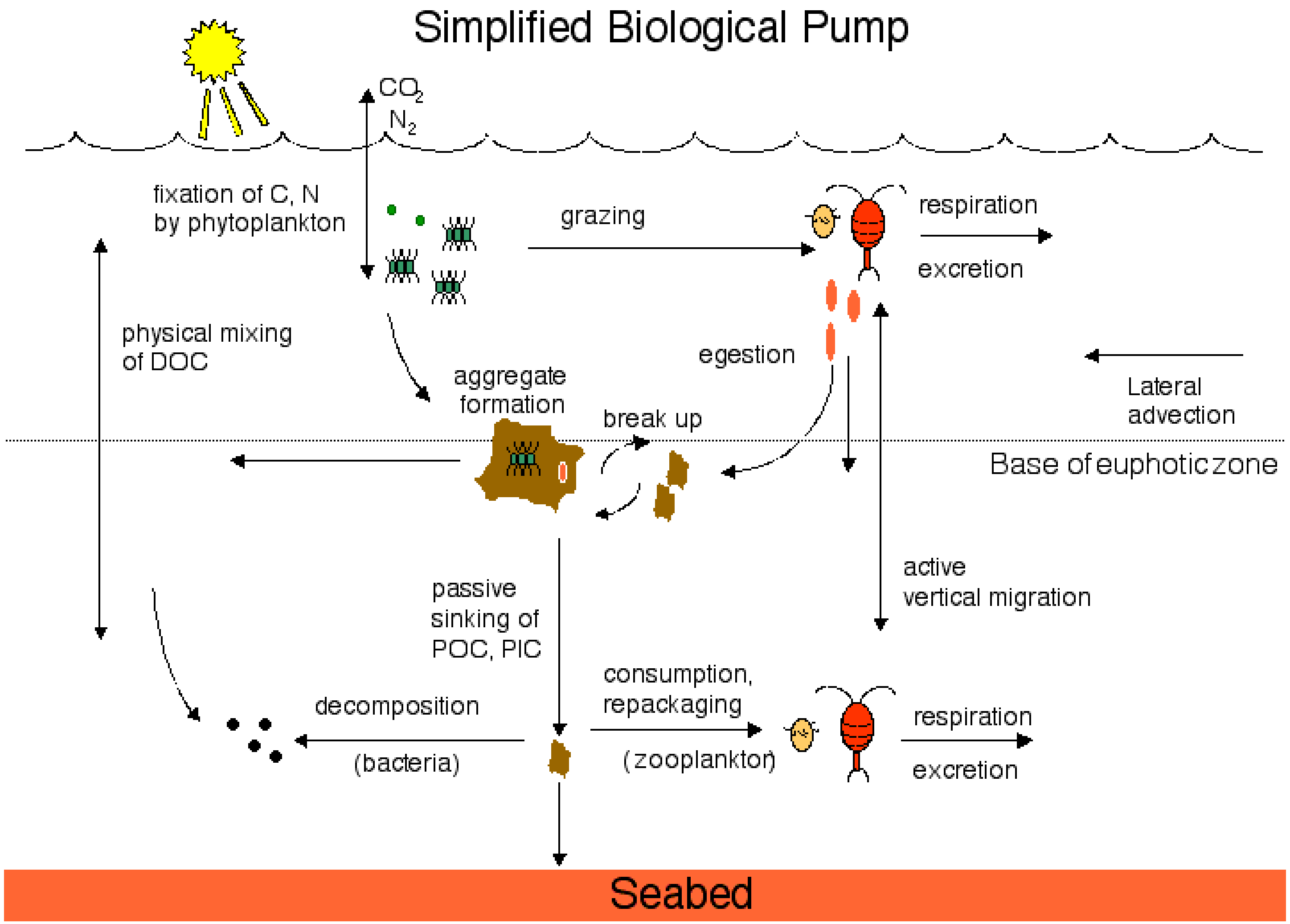
Buffer Factor (Revelle Factor):

$\Delta pCO_2/pCO_2 \approx 10\ \ \Delta DIC/DIC$



The Biological Pump

The „Biological Pump" mechanism summarises all processes transferring fixed carbon (CO_2) to the interior of the ocean.



Biological Pump Working Group Summary, Chair: Dave Karl, Rapporteur: Debbie Steinberg

Possible CE-Approaches

- Enhance CO_2 uptake by the ocean:

1) Biological uptake (e.g. ocean fetilization)
2) Make the Ocean more alkaline, e.g. by adding lime (see below)

- Reduce „airborne fraction“ of CO_2

1) Improved mixing within the ocean (will be explained below)
2) Increase the effectivity of the „biological pump“

UPTAKE OF CO_2 BY THE OCEANS

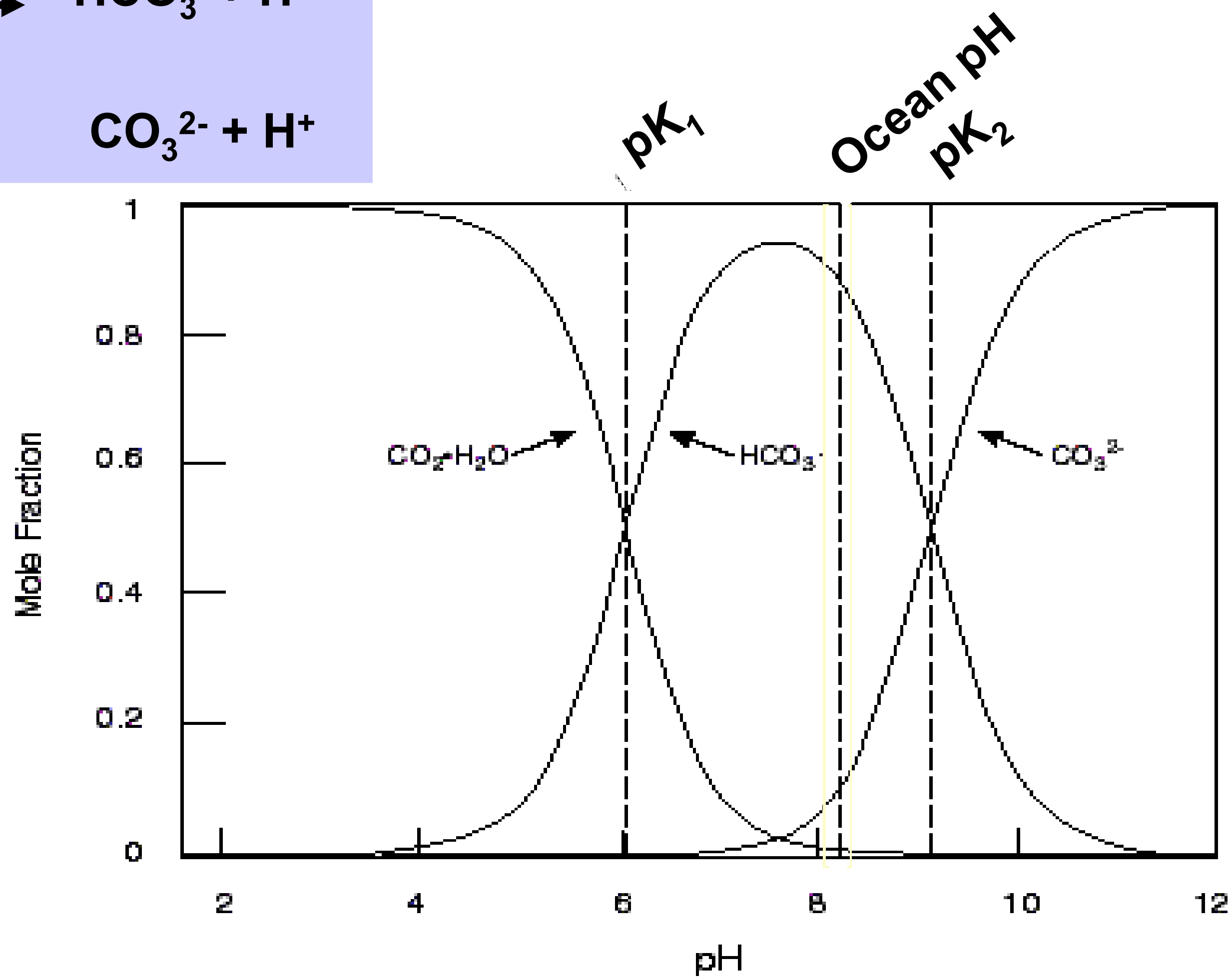
ATMOSPHERE $CO_2(g)$

$\downarrow\uparrow$

OCEAN $CO_2 \cdot H_2O$

$K_1 = 9 \times 10^{-7}$ M $\quad CO_2 \cdot H_2O \rightleftharpoons HCO_3^- + H^+$

$K_2 = 7 \times 10^{-10}$ M $\quad HCO_3^- \qquad CO_3^{2-} + H^+$



Net uptake:

$CO_2(g) + CO_3^{2-} \longrightarrow 2HCO_3$

Possible CE-Approach

Enhance CO_2 uptake by the ocean by making the sea water more alkaline

e.g. add limestone

Reactions of the Global Carbon Cycle to Changes (1)

How will additional CO_2 distribute to the reservoirs?

First idea:

Additional CO_2 will distribute itself according to reservoir size (i.e. 98.5% will go into the ocean).

Problem: Change of pH in the ocean (from present 8.2 – 8.4 to lower levels).

Described by the Revelle Factor ε:

$$\frac{\Delta\left[CO_2\right]_{Ocean}}{\left[CO_2\right]_{Ocean}} = \frac{\Delta\left[CO_2\right]_{Atm}}{\left[CO_2\right]_{Atm}} \cdot \frac{1}{\varepsilon}$$

$$\varepsilon = \frac{\dfrac{\Delta p\left(CO_2\right)}{p\left(CO_2\right)}}{\dfrac{\Delta \Sigma CO_2}{\Sigma CO_2}} \approx 9 \ldots 14$$

Reactions of the Global Carbon Cycle to Changes (2)

Ocean: (CO_2, carbonate, bicarbonate) $M_{ocean} \approx 40000$ GtC

Atmosphere (CO_2) $M_{atm} \approx 800$ GtC

The carbon reservoir in the ocean is about 50-times larger than the carbon reservoir in the atmosphere.

Naively, one would expect, that on the long run (actually this would take ≈2000 years) the additional (anthropogenic) CO_2 would distribute according to $M_{atm}:M_{ocean} \approx 1:50$ between atmosphere and ocean, thus:
Δx_{CO2} would reduce from ≈ 250ppm (if all CO_2 was in the atm.) to $\Delta x_{CO2}/50 \approx 5$ppm (i.e. we would return to 280+5ppm)

In Reality the capacity of the ocean is reduced by the Revelle factor $\varepsilon \approx 10$, thus Δx_{CO2} reduces from ≈ 250ppm to $\Delta x_{CO2} \cdot \varepsilon/50 \approx 50$ppm (i.e. we would return to 280+50 ≈ 330ppm)

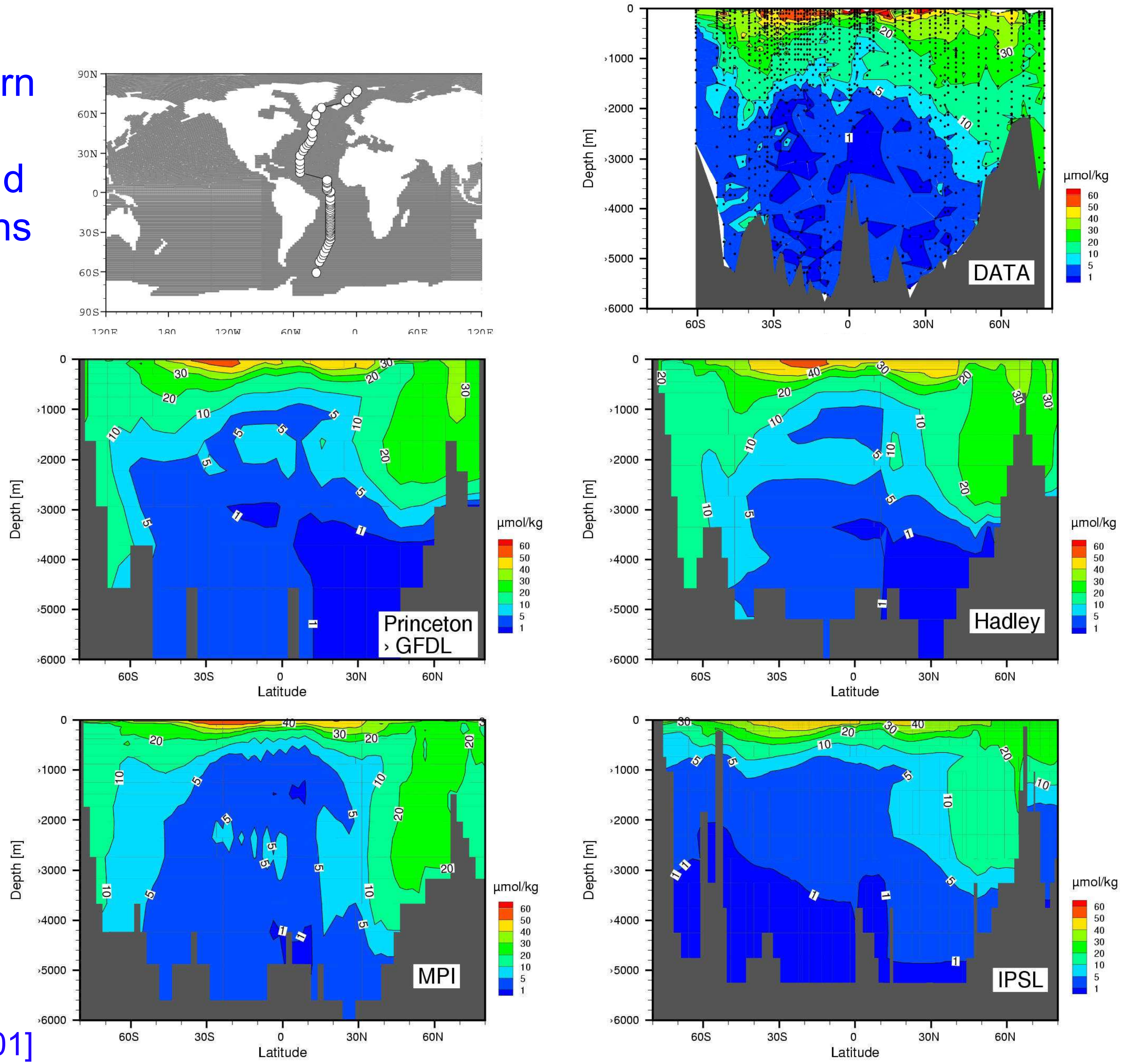
Possible CE-Approach

Enhance exchange between ocean surface-water and ocean deep water to shorten the 2000 year time constant for natural mixing.

e.g. „Ocean Pipes“ Lovelock and Rapley

James E. Lovelock, Chris G. Rapley, Ocean pipes could help the Earth to cure itself, NATURE 449, 27 September 2007

Anthropogenic Carbon in Western Atlantic Observations and Model Simulations



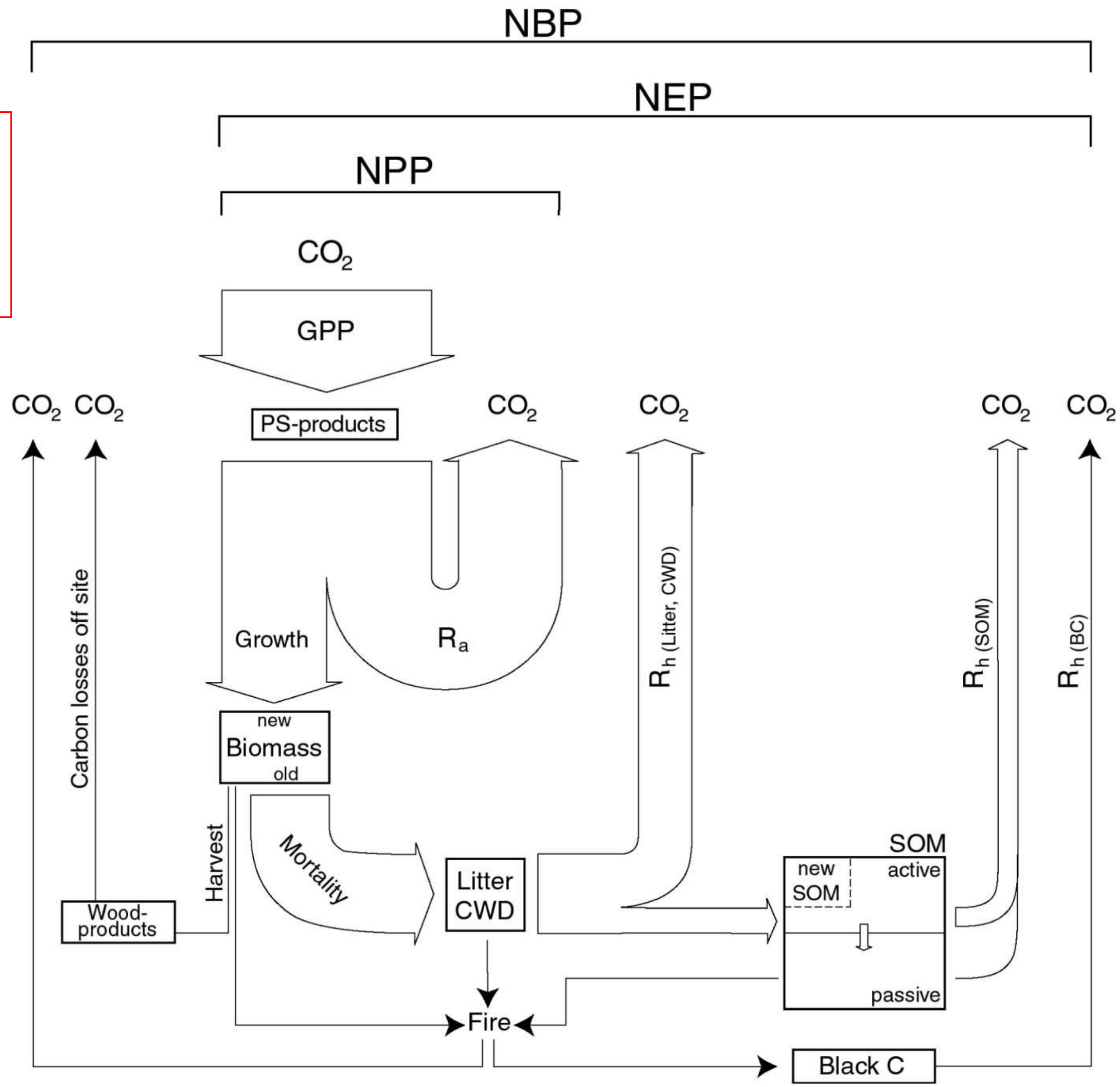
OCMIP [Orr et al., 2001]

Carbon Fluxes in The Terrestrial Biosphere

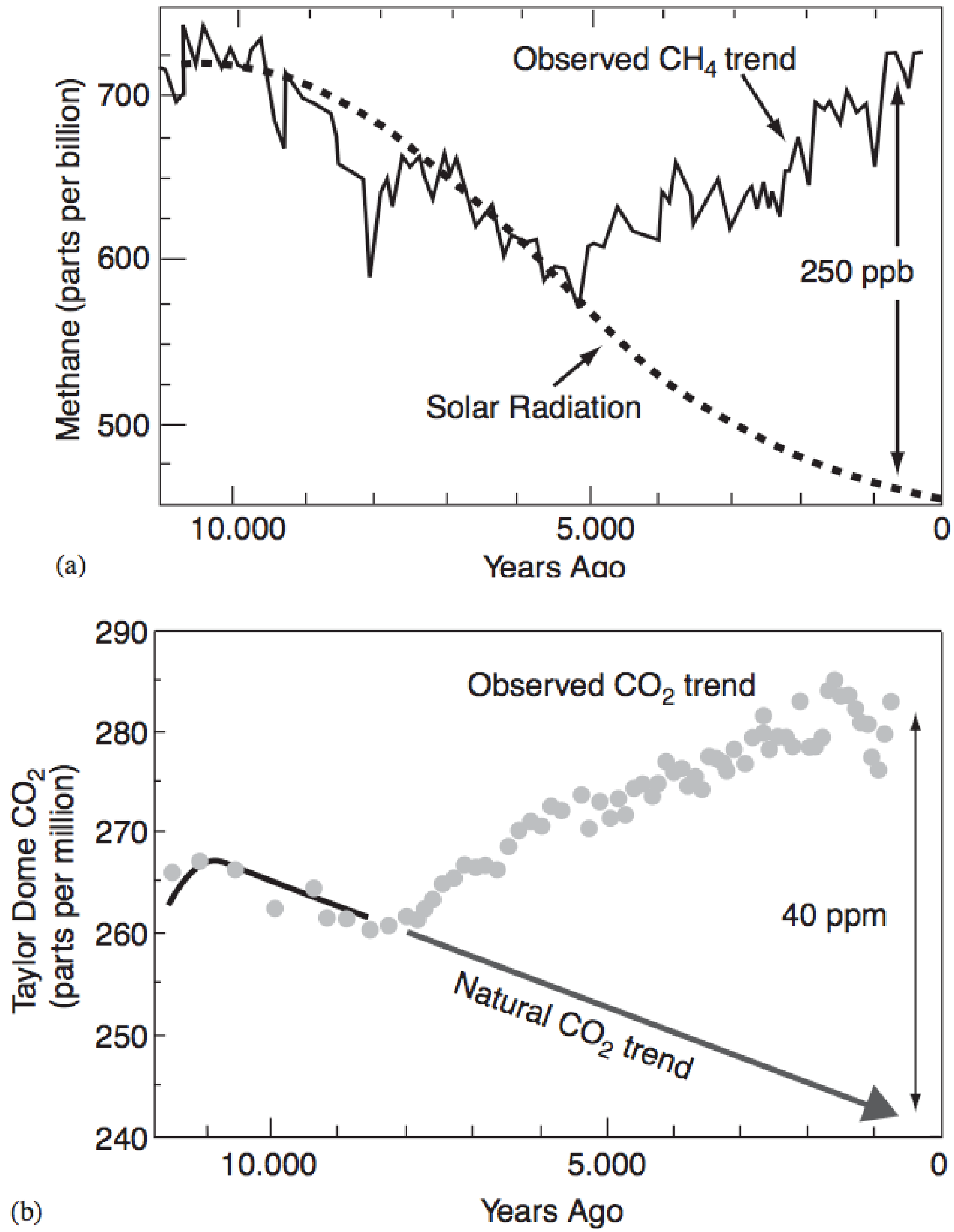
NBP: Net Biosphere Productivity

NEP: Net Ecosystem Production

NEP: Net Primary Production



Anthropogenic Effects in the Early Holocene?



Ruddiman, Climatic Change, 2003

Direct Response of Carbon Cycle to Anthropogenic Perturbation (up to now)

- Atmosphere: Increase from 280ppm (1860) to ~380ppm (2005)
- Ocean:
  - Dissolution into surface waters
  - Advection and mixing into the interior
  - Marine biota nutrient limited
- Land:
  - Direct response (“CO_2 fertilization”) disputed
  - Evidence for changes:
    - “Greening trend”
    - Mauna Loa seasonal amplitude increase
  - Other effects (indirect or concidental):
    - N-fertilization
    - Regrowing forests
    - Climate

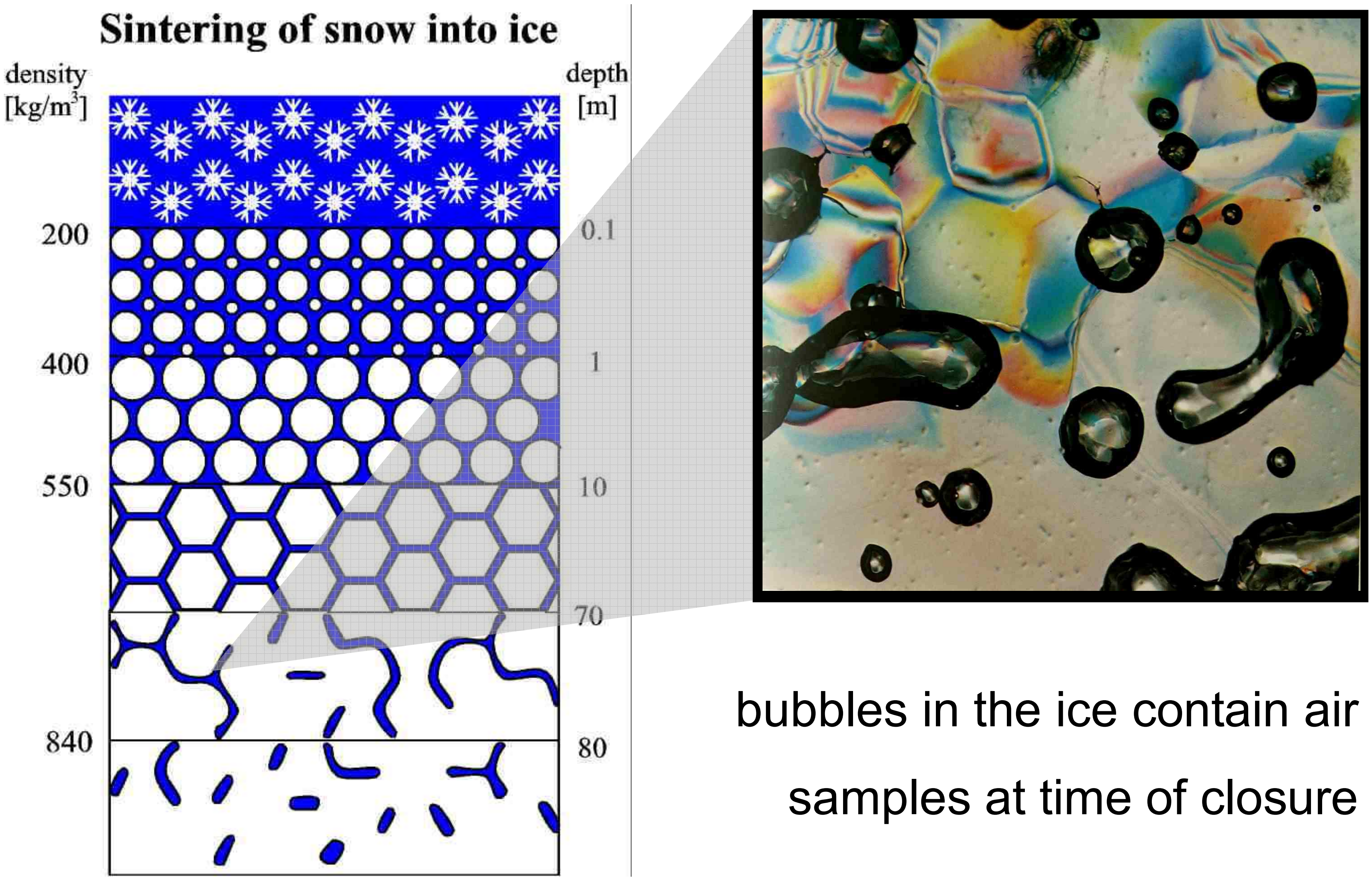
Paleoclimate

How to measure CO_2 before 1957?

Answer: Natural Archives

In the case of CO_2: Ice Cores

From Snow to Ice

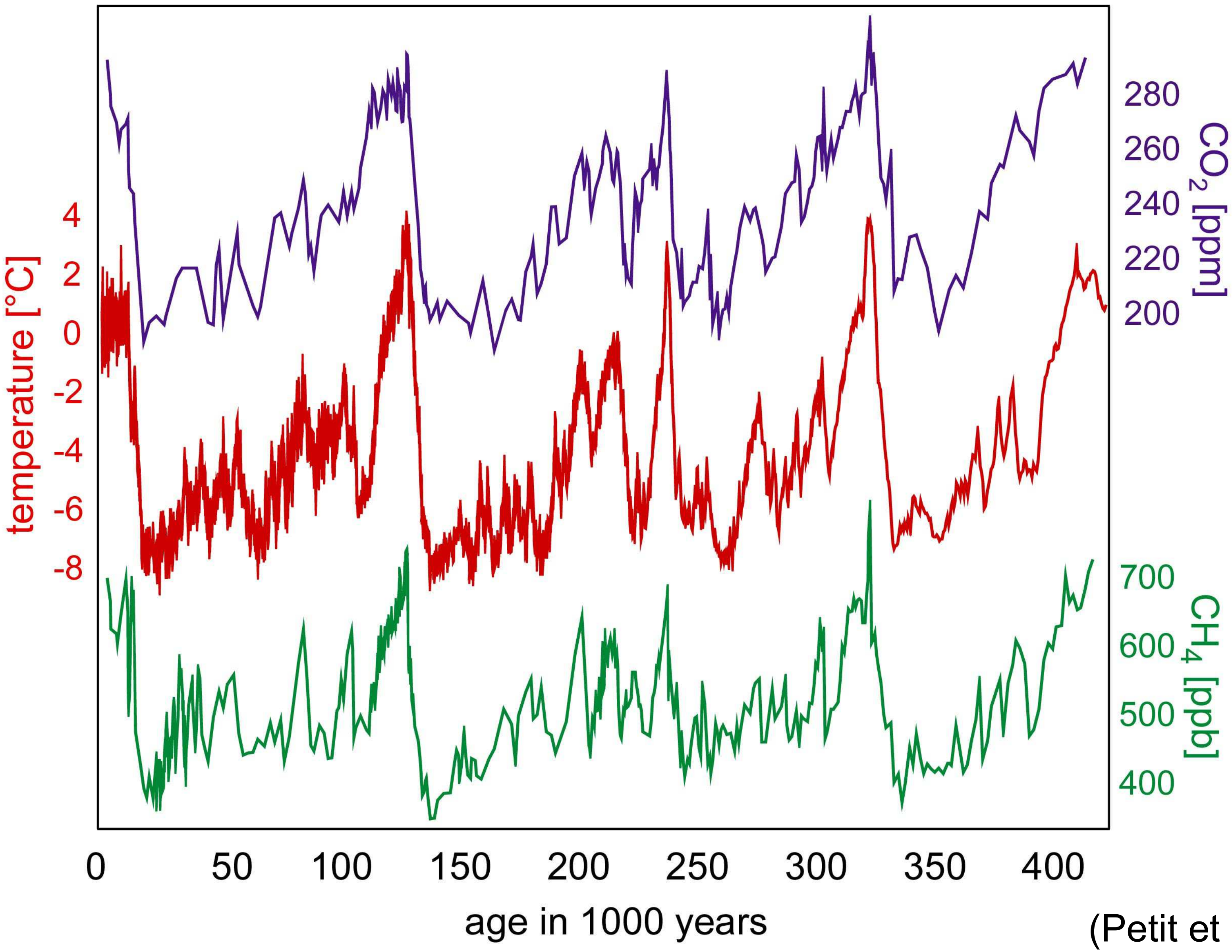


bubbles in the ice contain air

samples at time of closure

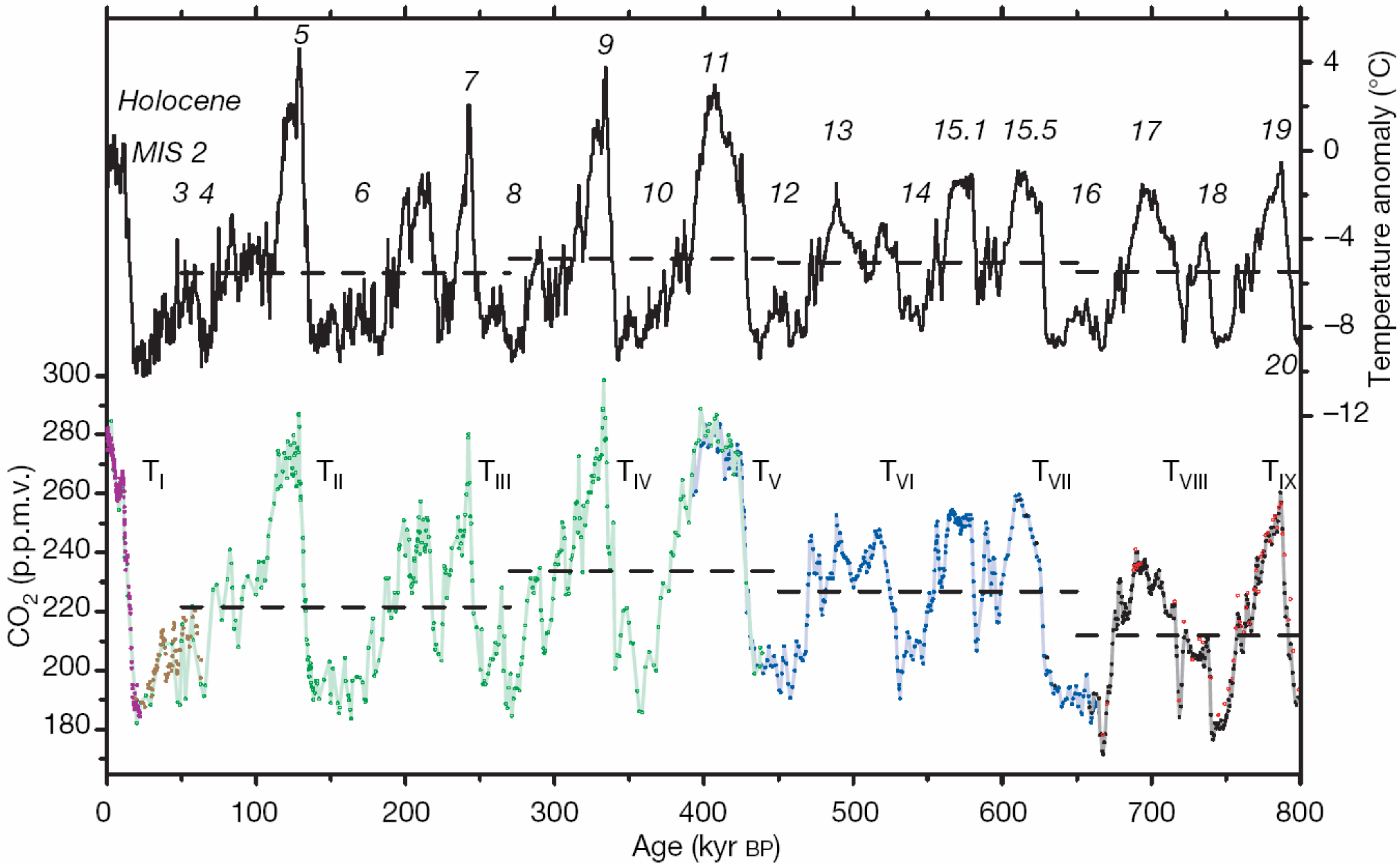

Ice Core

Time Series of CO_2, CH_4, & Isotope Temperature from Ice Cores



(Petit et al., 1999)

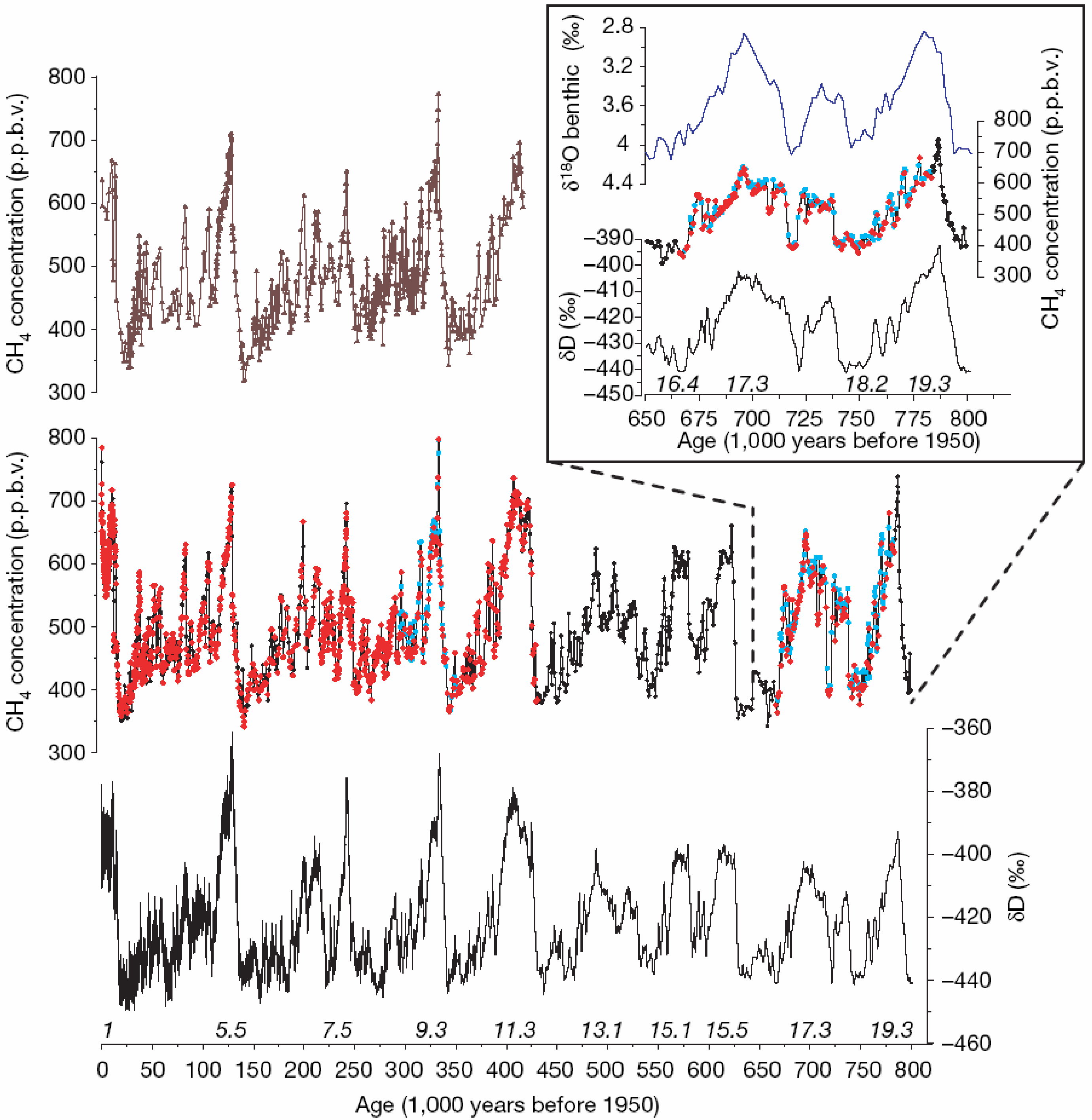
Time Series of CO_2, and Isotope Temperature from the European Project for Ice Coring in Antarctica (EPICA) Dome C Ice Core



Dieter Lüthi et al. 2008, Nature 453, 379-382

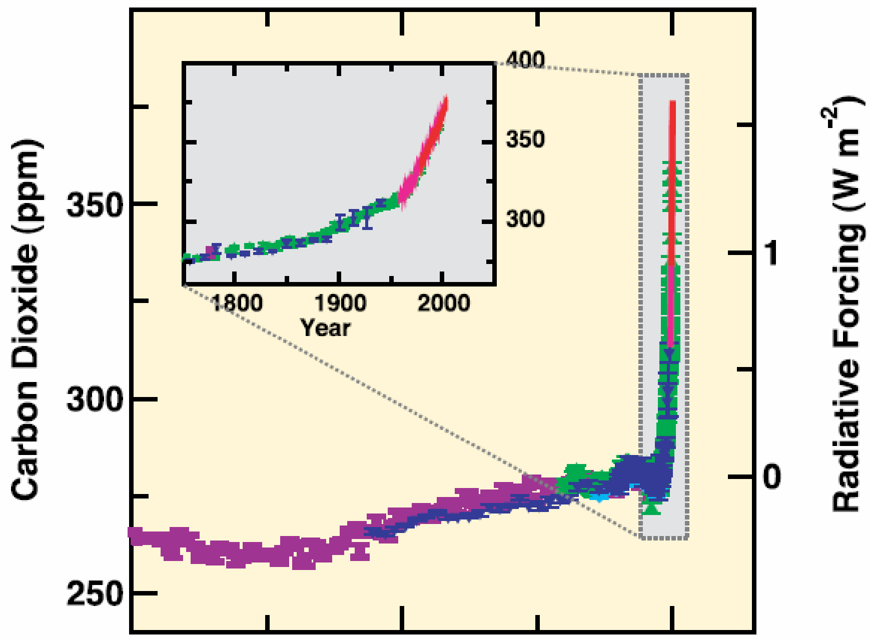
Time Series of CH_4, and δD from the EPICA Dome C Ice Core (Antarctica)

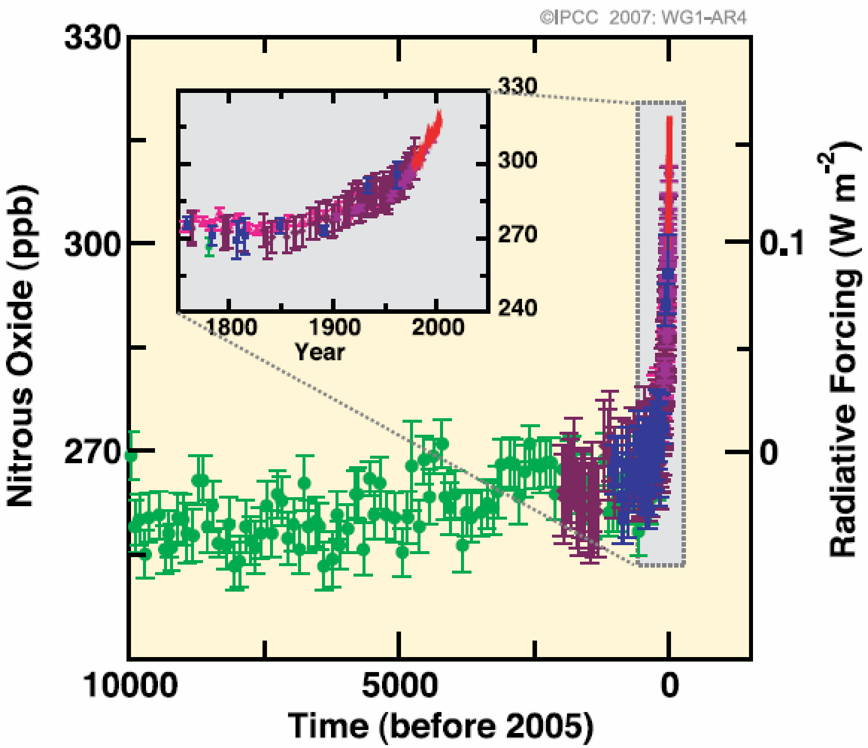
Figure 1: Methane records and EPICA/Dome C δD. Bottom to top: dD record9; EDC methane record (previously published data2, black diamonds; new data from LGGE, red diamonds; new data from Bern, blue dots); Vostok methane record1. Marine Isotope Stage numbering is given at the bottom of each interglacial.
Insert: expanded view of the bottom section of EDC: dD values9 (black line), CH4 (black line) from EDC and stack benthic d18O values (blue line)19 for the period from MIS 16 to 20.2, on their respective age scales.
d18O5[(18O/16O)sample/(18O/16O)standard] – 1, where standard is vPDB;
dD5[(D/H)sample/(D/H)standard] – 1 where standard is SMOW.
Vol 453, 15 May 2008, doi:10.1038/nature06950

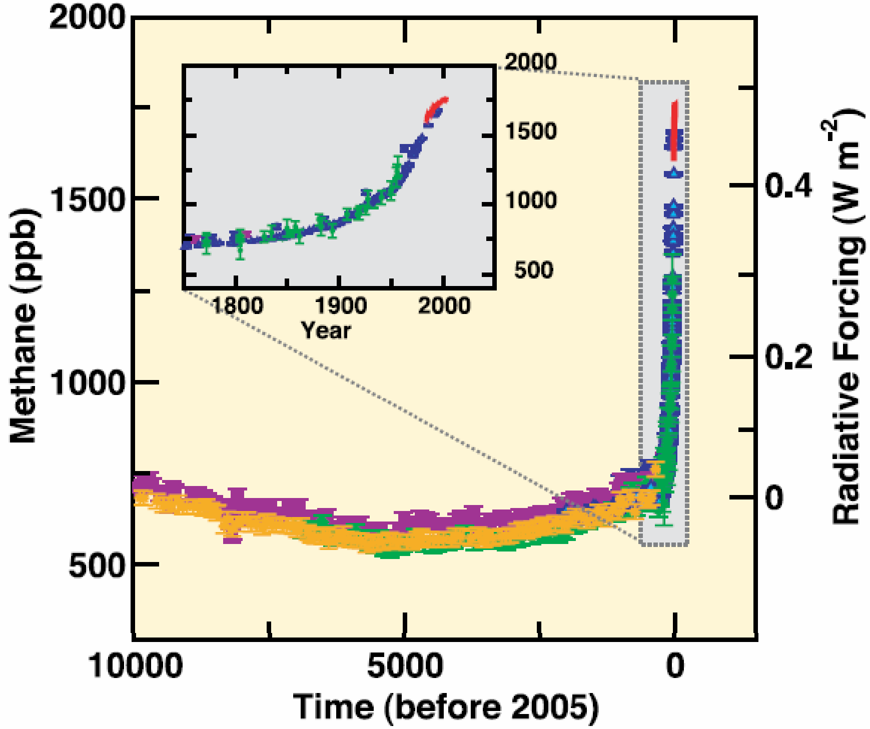


Atmospheric CO_2, CH_4, and N_2O and Climate Forcing from Ice Cores and Measurements

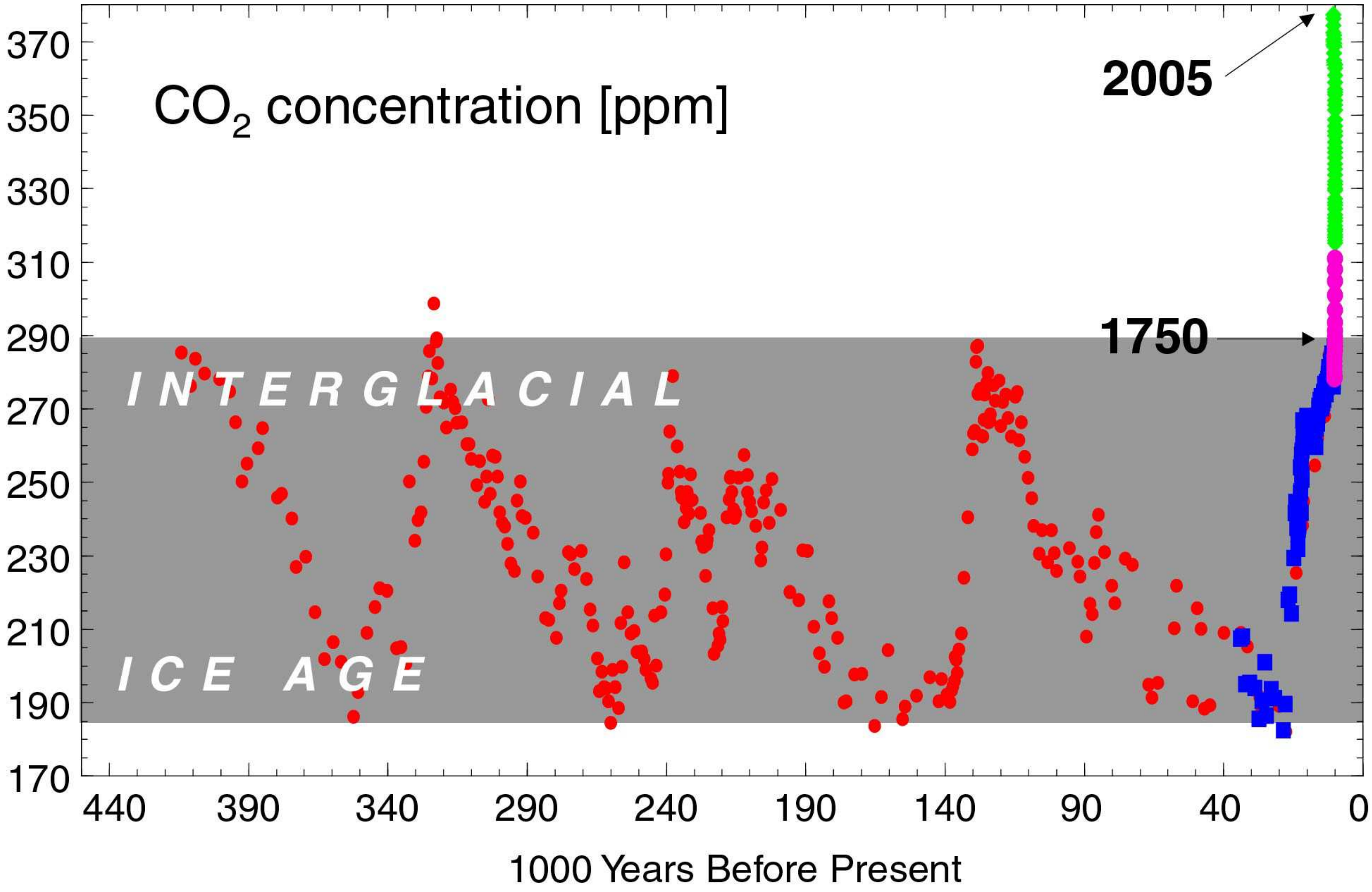
IPCC 4th Assessment Report, 2007





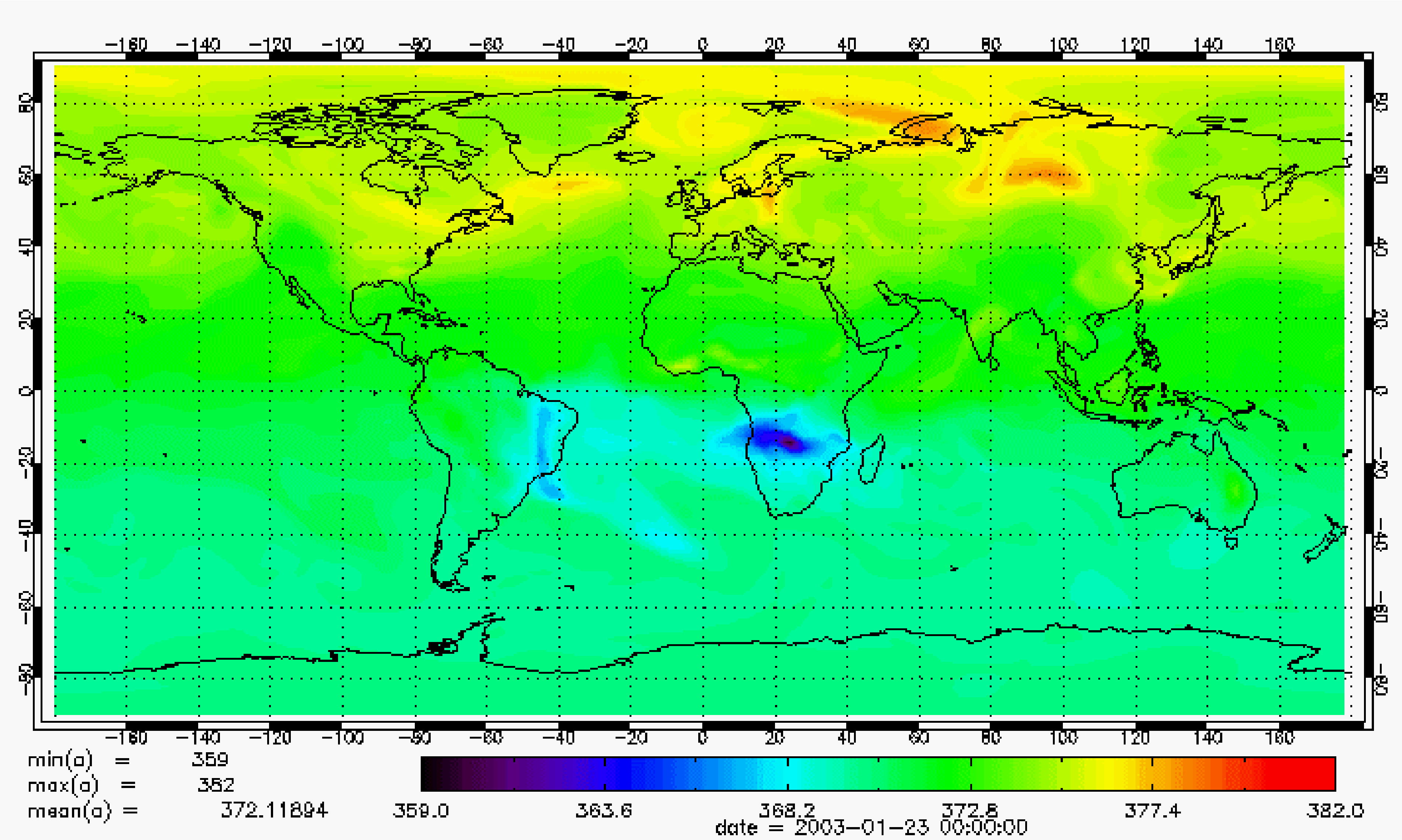


CO_2 higher than ever during the last 650,000 years



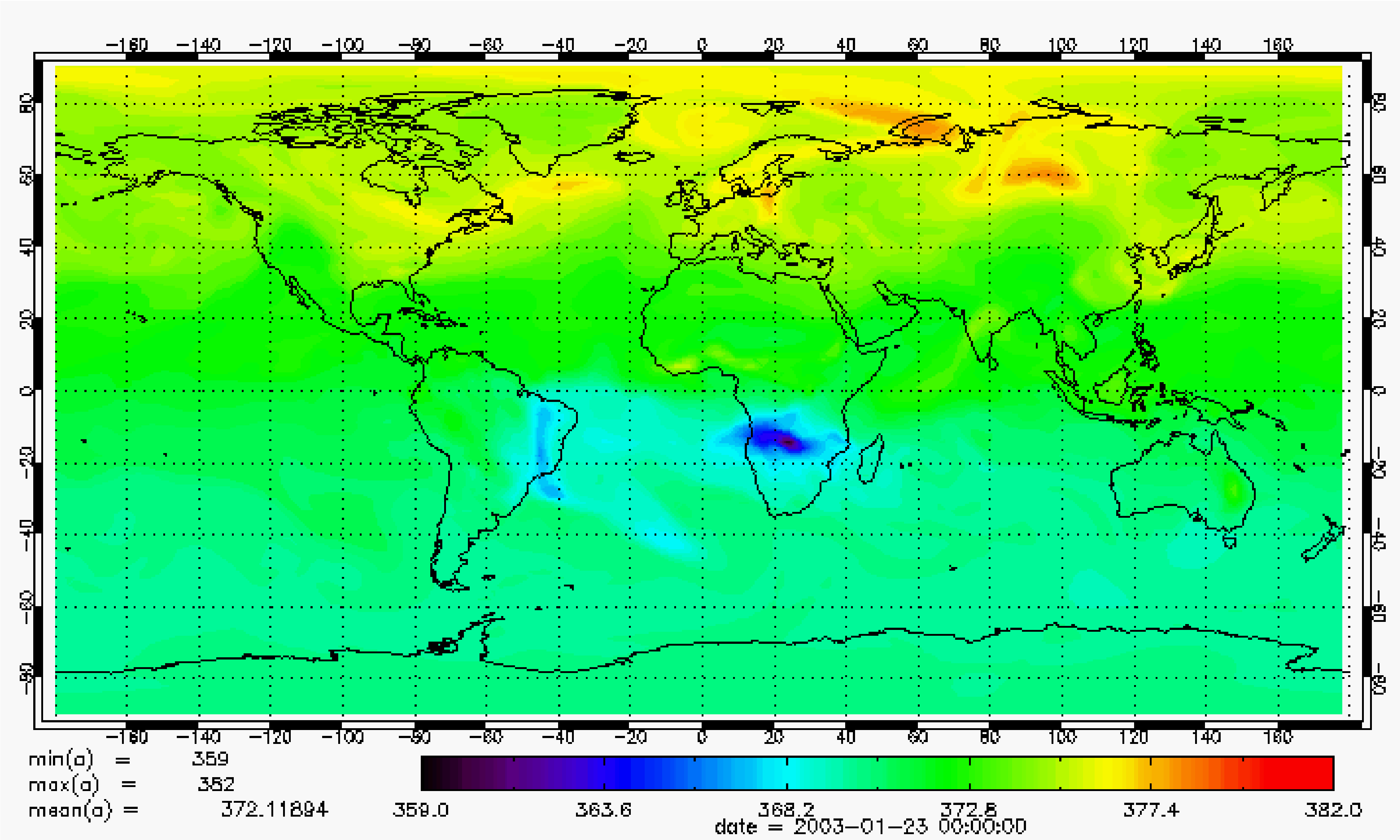
(Petit et al, 1999, Bern, NOAA)

CO_2 Model Jan/Feb 2003



Model by Koerner and Heimann, 2003

CO_2 Model – Annual Variation



Model by Koerner and Heimann, 2003

The Carbon Cycle on Geological Time Scales

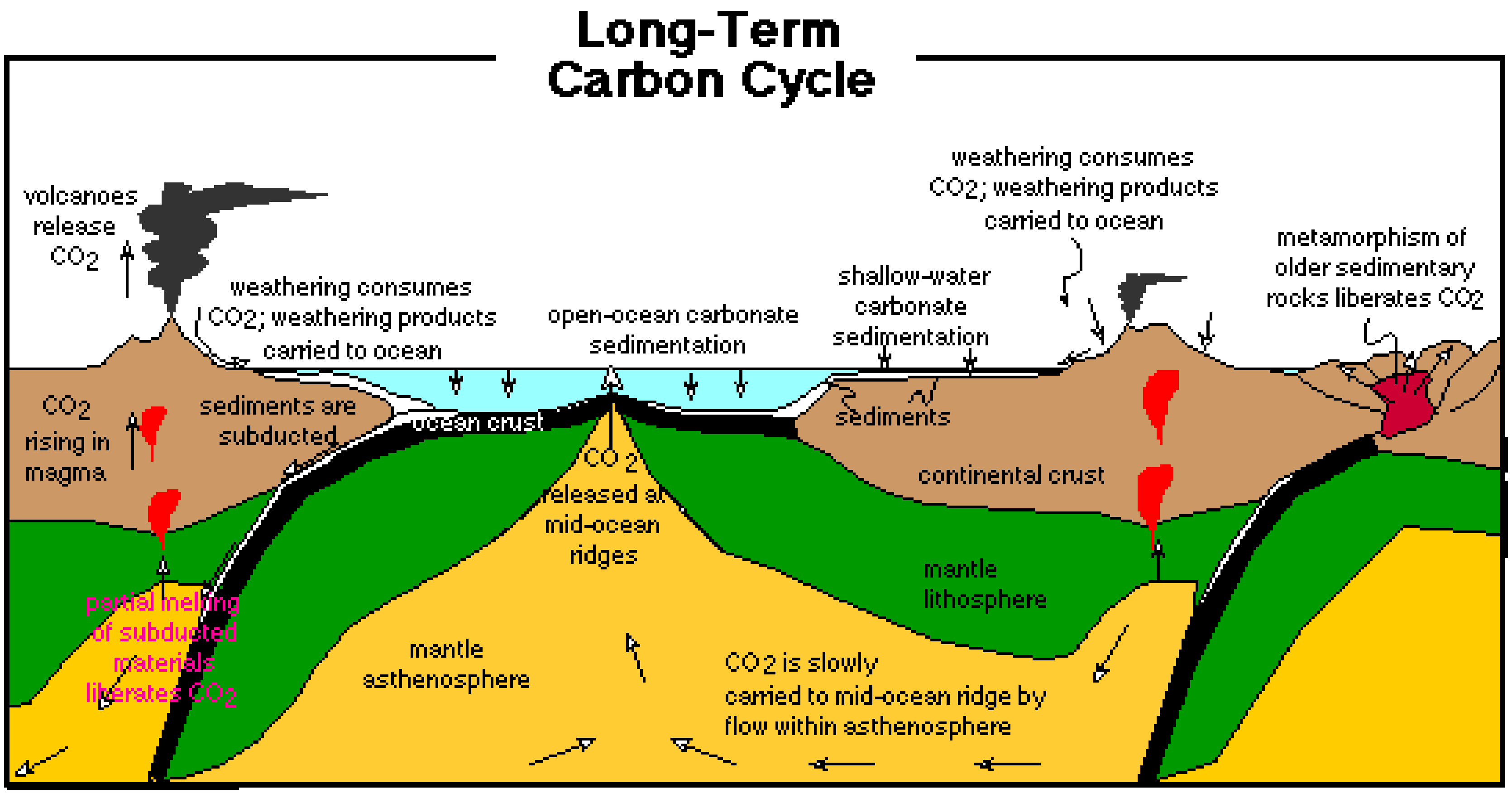


Figure 7.3.1 Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation exracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly — if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

Geological Time Scales: GEOCARB III Model

$$CO_2 + CaSiO_3 \leftrightarrow CaCO_3 + SiO_2$$

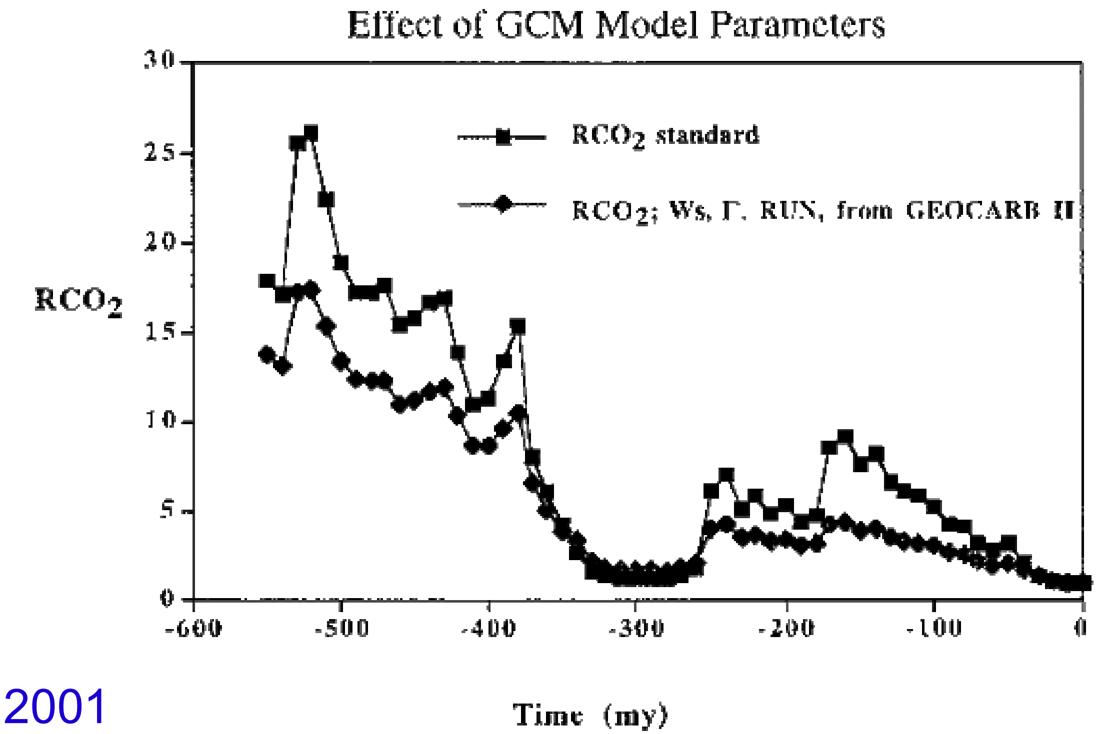
$$CO_2 + MgSiO_3 \leftrightarrow MgCO_3 + SiO_2$$

Ca and Si weathering

$$CH_2O + O_2 \leftrightarrow CO_2 + H_2O$$

Organic carbon formation

Reconstructed atmospheric CO_2 levels (Present: $RCO_2 = 1$)



Berner and Kothavala, J. Am. Sci., 2001

Possible CE-Approaches

Enhance CO_2 uptake by soil

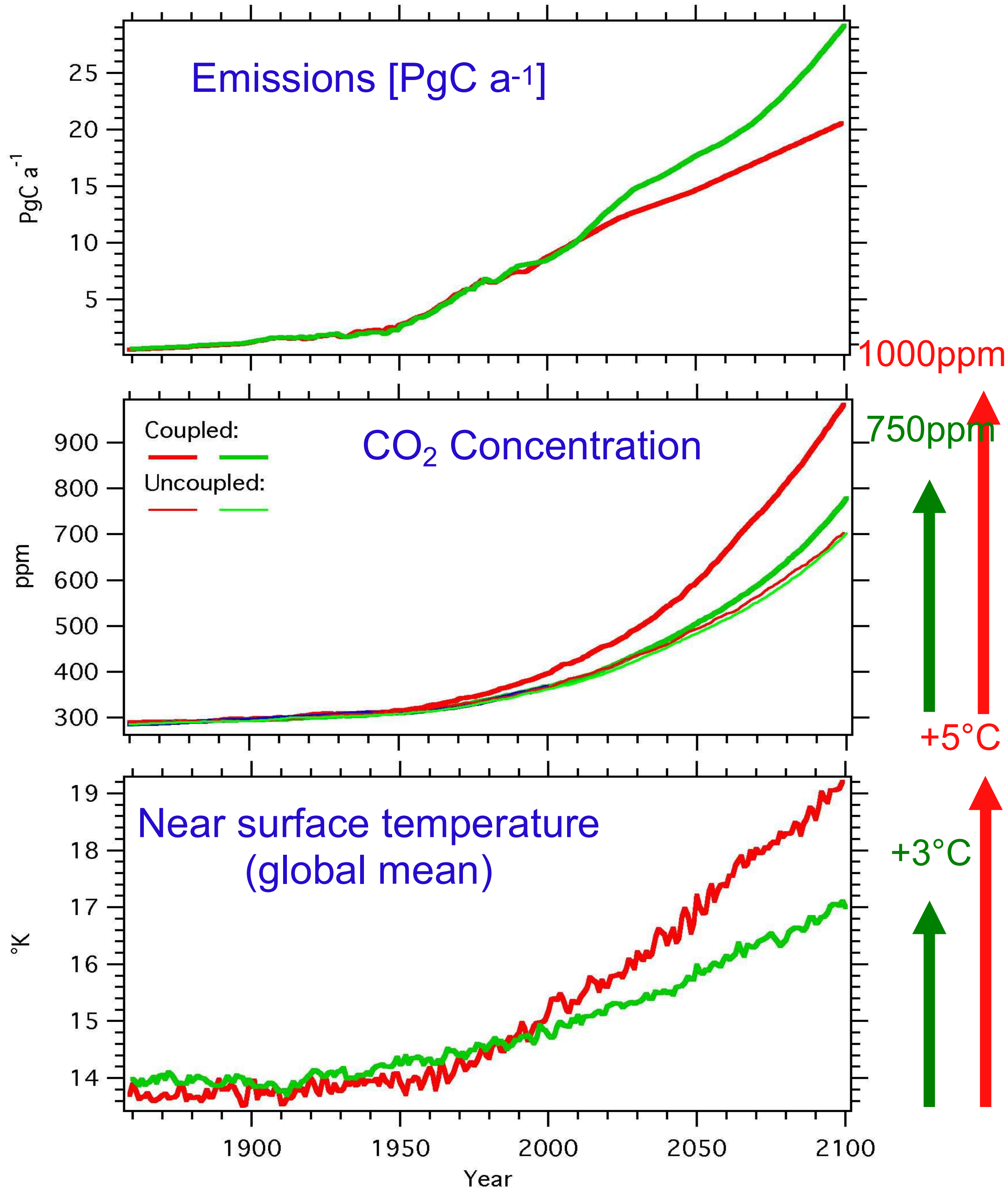
1) Enhance weathering and thus CO_2 uptake by soil

2) Make soils more alkaline
   e.g. add limestone

The Future: First Scenario Simulations with Coupled Carbon Cycle - Climate Models

Hadley Modell

IPSL Modell



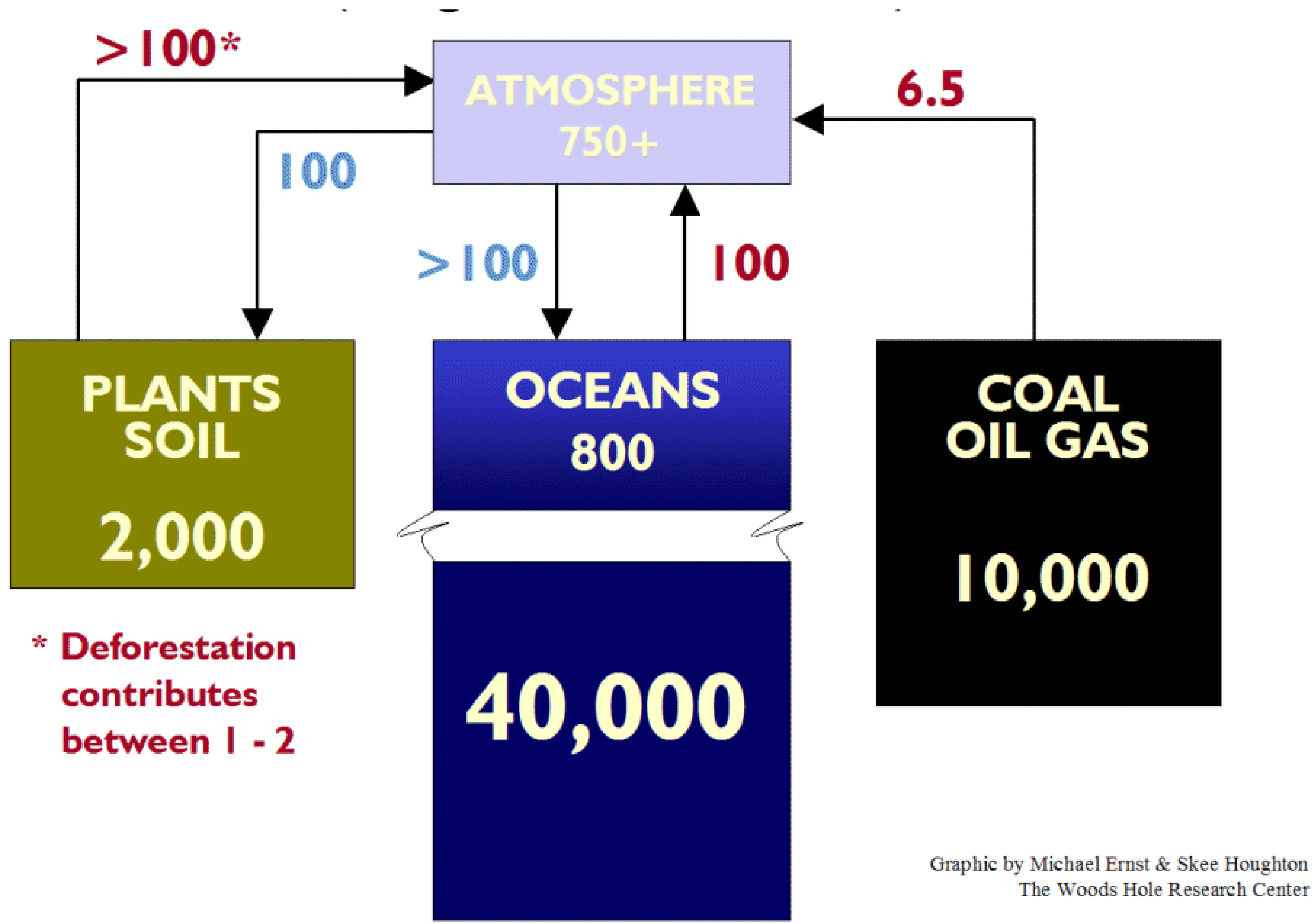
Cox et al. 2001,
Dufrene et al., 2001
IPCC 2001

Summary

- The carbon cycle has a strong influence on our climate (both, in natural changes and anthropogenic changes)
- Important carbon reservoirs are the sediments, the ocean, the land biomass, and the atmosphere
- Time constants in the carbon cycle range from years to 10^5 years
- Oceans get more acidic → less carbon uptake
- The role of the biomass is unclear

The Global Carbon Cycle

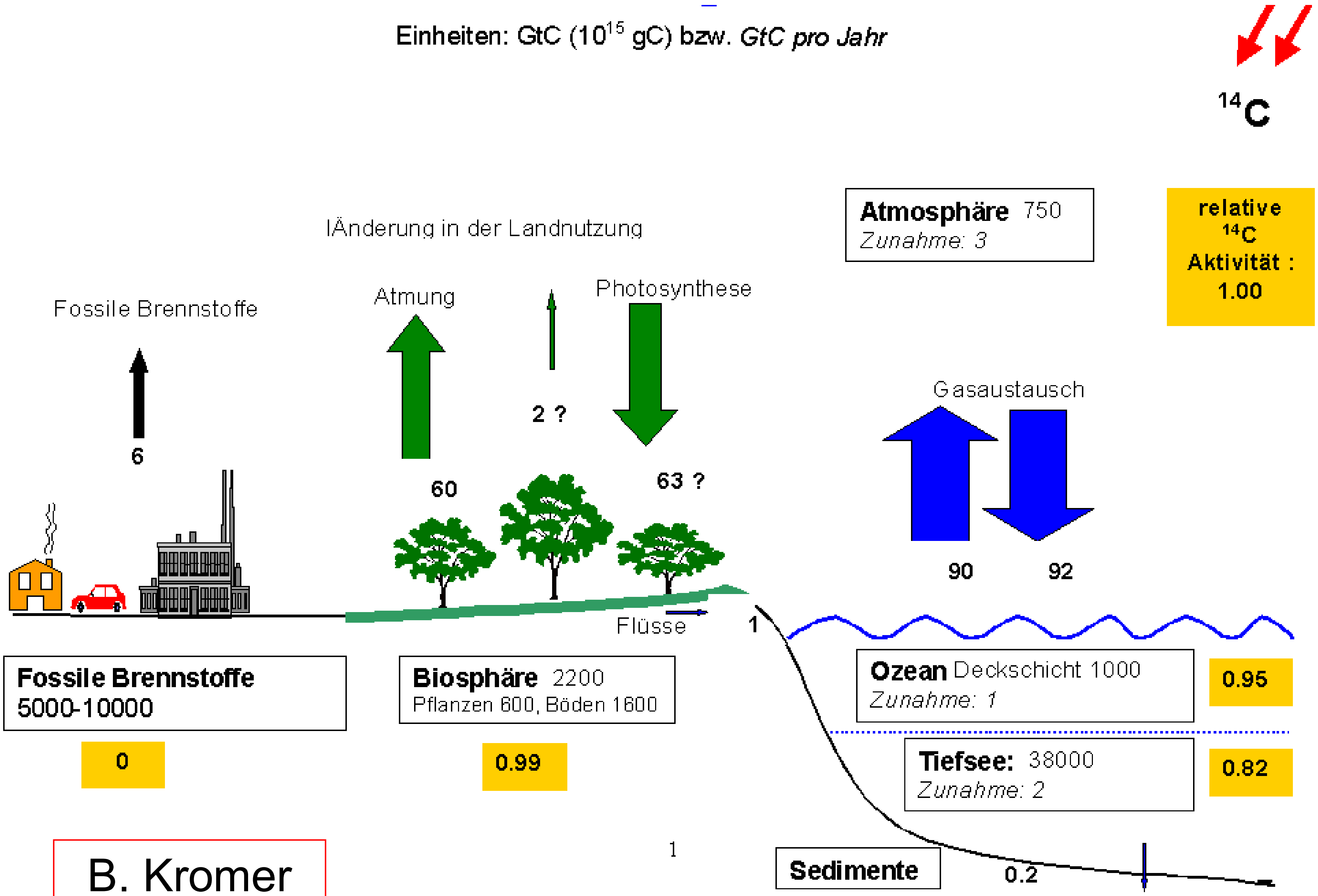
Approximate Reservoir sizes in Gt (10^{12}kg or 10^{15}g or petagram, Fluxes in Gt/a)



http://whrc.org/carbon/index.htm

The Global Carbon Cycle - Quantitative

Einheiten: GtC (10^{15} gC) bzw. *GtC pro Jahr*



B. Kromer