IT'S ABOUT TIME

Characteristic times in biogeochemistry and climate

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BROOKHAVEN NATIONAL LABORATORY

Symposium on biogeochemical cycling and climate

In honor of Henning Rodhe on the occasion of his retirement from the chair of Chemical Meteorology

Stockholm University

May 23, 2008

IT'S ABOUT TIME

TOPICS

Turnover times of atmospheric aerosols

Turnover time of excess atmospheric CO_2

Characteristic time of Earth's climate system

TURNOVER TIMES OF ATMOSPHERIC AEROSOLS

I shot an ***aerosol particle*** into the air, and then
It fell to earth, I knew not where (***or when***);

Apologies to Longfellow

Source-receptor relations in acid deposition

Aerosol influences on climate

A note on the concepts of age distribution and transit time in natural reservoirs

By BERT BOLIN and HENNING RODHE, *Institute of Meteorology, University of Stockholm, Sweden*[1]

Tellus XXV (1973)

reservoirs. We shall further limit the present study to steady state conditions, i.e. we assume that the total mass and the statistical distributions studied do not vary with time. Such a

Participants at the International Symposium on Sulfur in the Atmosphere, Dubrovnik, September 1977

BUDGETS AND TURN-OVER TIMES OF ATMOSPHERIC SULFUR COMPOUNDS

HENNING RODHE

Atmospheric Environment Vol. 12. 1978.

Steady-state conditions:

Turnover time: $\tau_{t\text{-}o} = M / F$

M = mass in reservoir

F = flux into (or out of) reservoir

Turnover times:

SO_2	25 h
SO_4^{2-}	80 h
Sulfur ($SO_2 + SO_4^{2-}$)	50 h

Sulfate yield: 30%

Residence times in reservoirs under non-steady-state conditions: application to atmospheric SO_2 and aerosol sulfate

By STEPHEN E. SCHWARTZ, *Atmospheric Sciences Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.*

Tellus (1979)

Non–steady-state conditions:

Turnover time: $\tau_{\text{t-o}} = \overline{M} / \overline{F}$

M = mass in reservoir

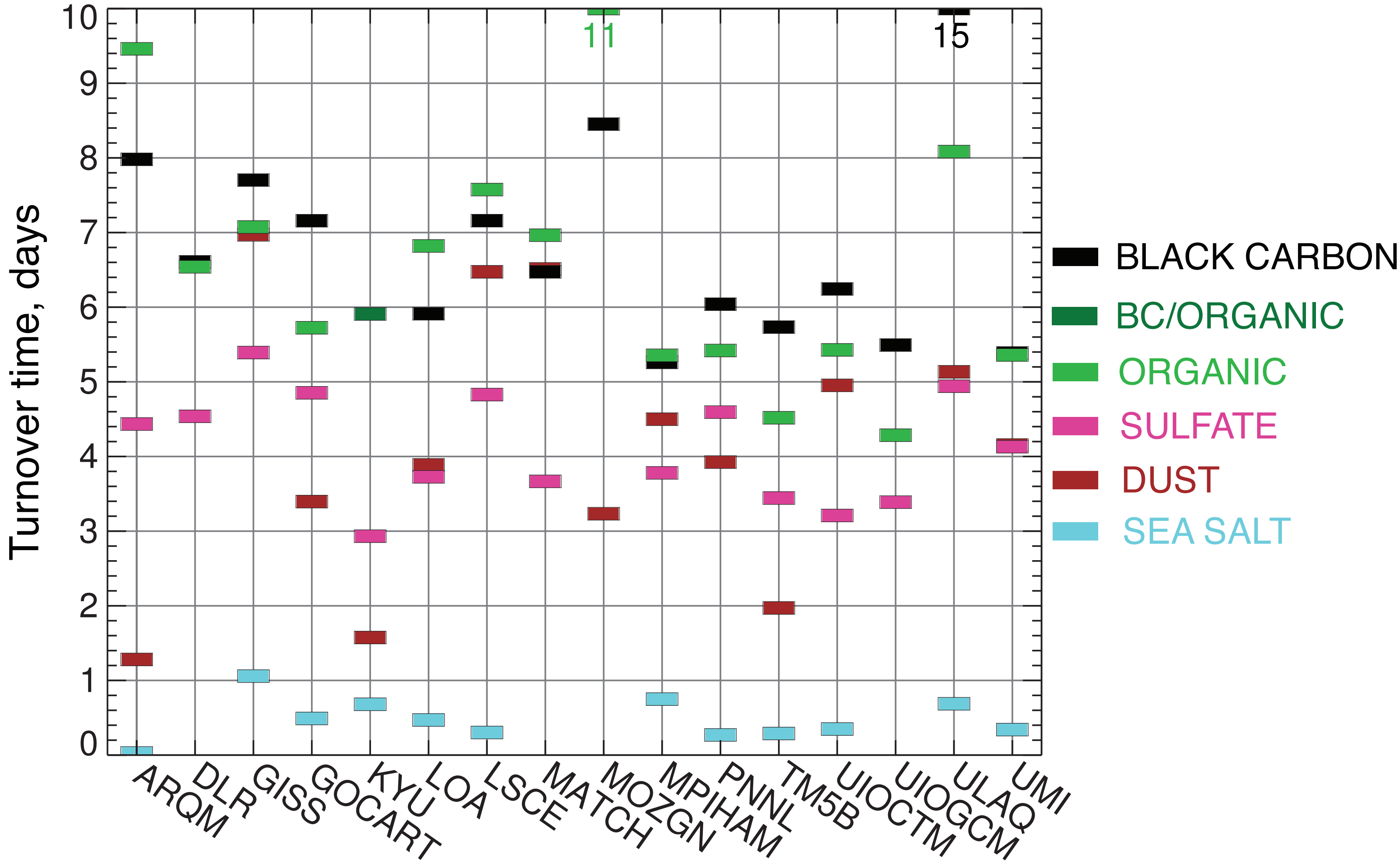
F = flux ***out of*** reservoir

Averages are taken over suitably long periods.

Long-time averages yield stable, representative turnover times.

TURNOVER TIME AS INTENSIVE VARIABLE

Five aerosol species in 16 global chemical transport models



AEROCOM, Textor et al., ACP, 2006

Characterize and compare processes in chemical transport models.

Turnover time displays ***wide model-to-model variance***.

Sulfate residence time close to Rodhe (1978) value 80 h = 3.3 days

TURNOVER TIME OF EXCESS ATMOSPHERIC CO_2

I emit a kilogram of CO_2 into the air, and then

It falls to earth: Can you tell me when?

Decision making on energy and climate change

A Comparison of the Contribution of Various Gases to the Greenhouse Effect

HENNING RODHE SCIENCE, VOL. 248 8 JUNE 1990

Impulse response function

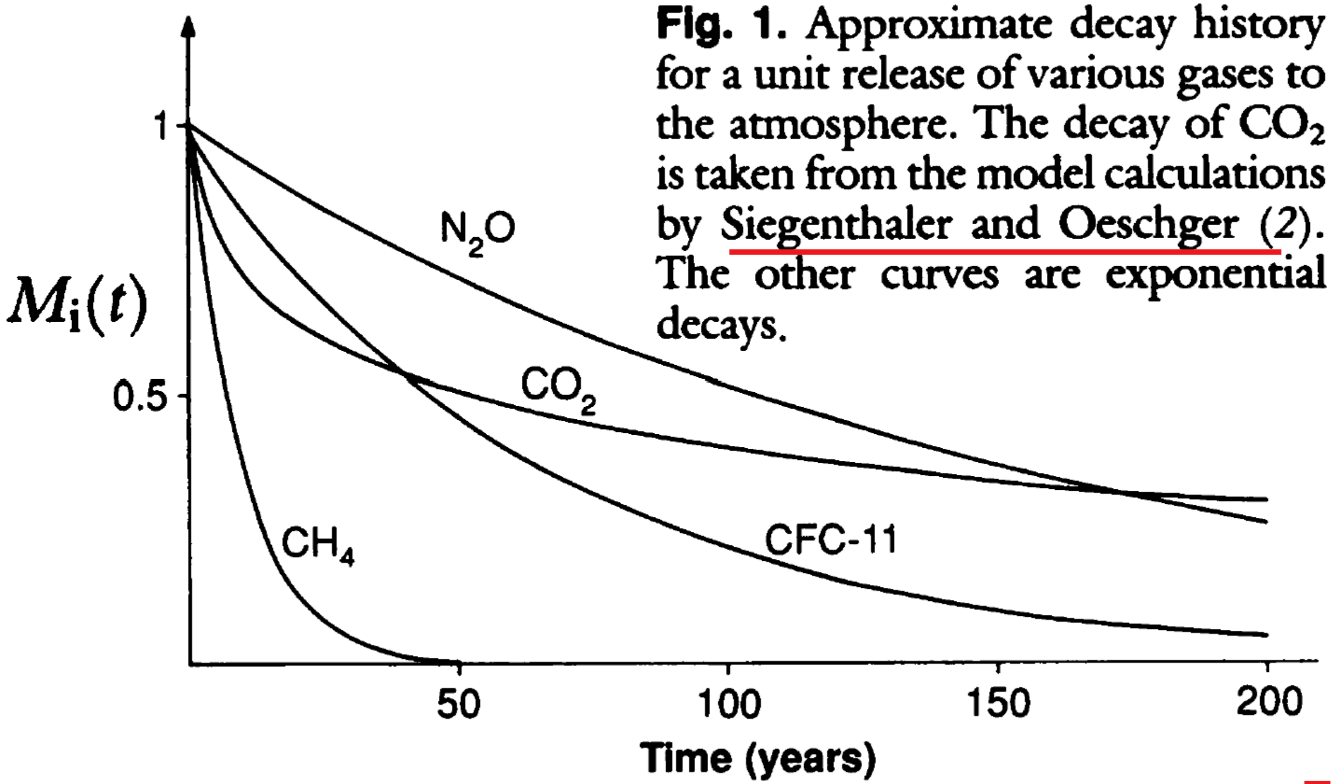
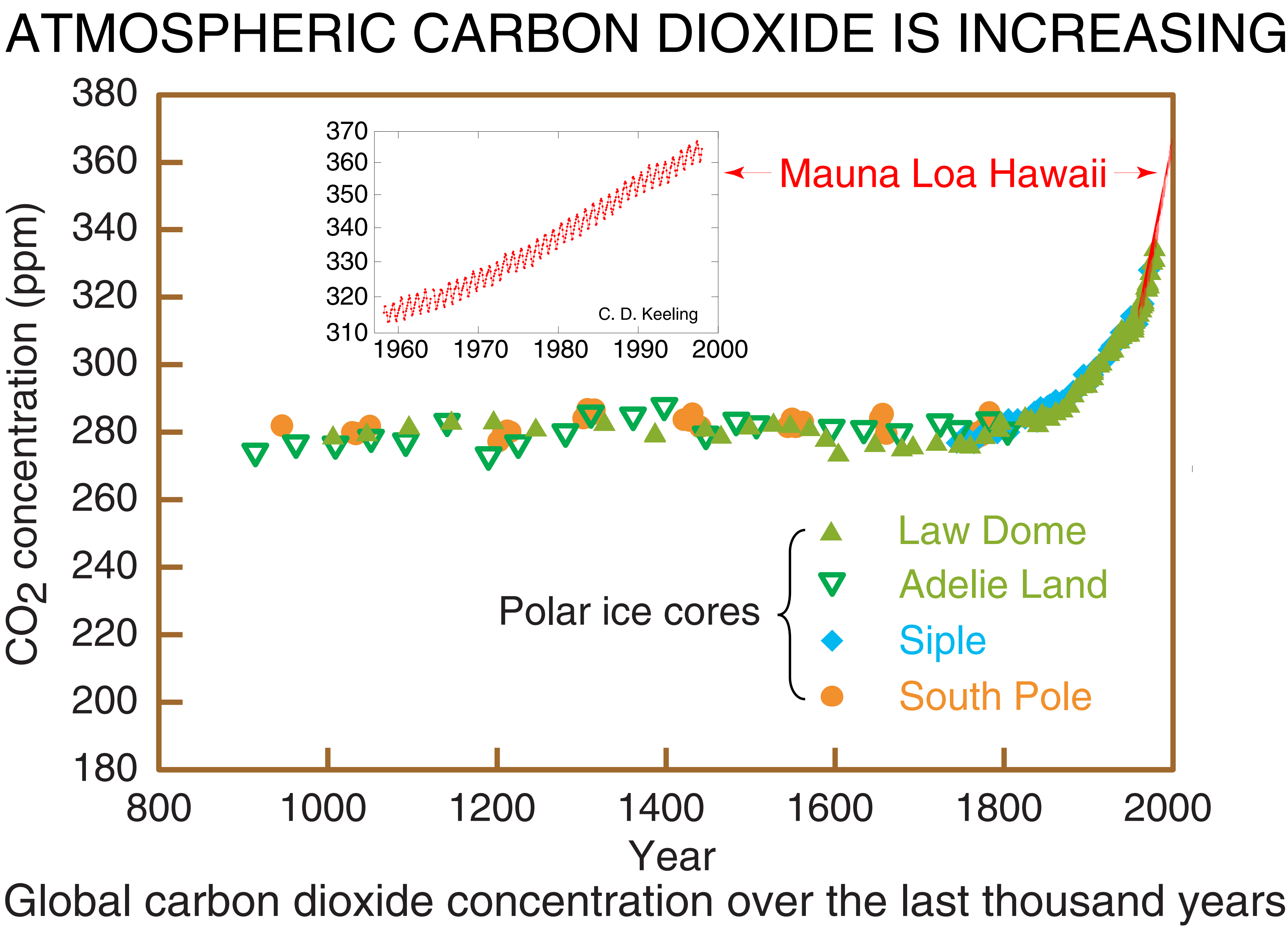


Fig. 1. Approximate decay history for a unit release of various gases to the atmosphere. The decay of CO_2 is taken from the model calculations by Siegenthaler and Oeschger (*2*). The other curves are exponential decays.

$$AG_i = \int_0^T k_i M_i(t)dt = k_i \int_0^T M_i(t)dt$$

Forcing per unit mass

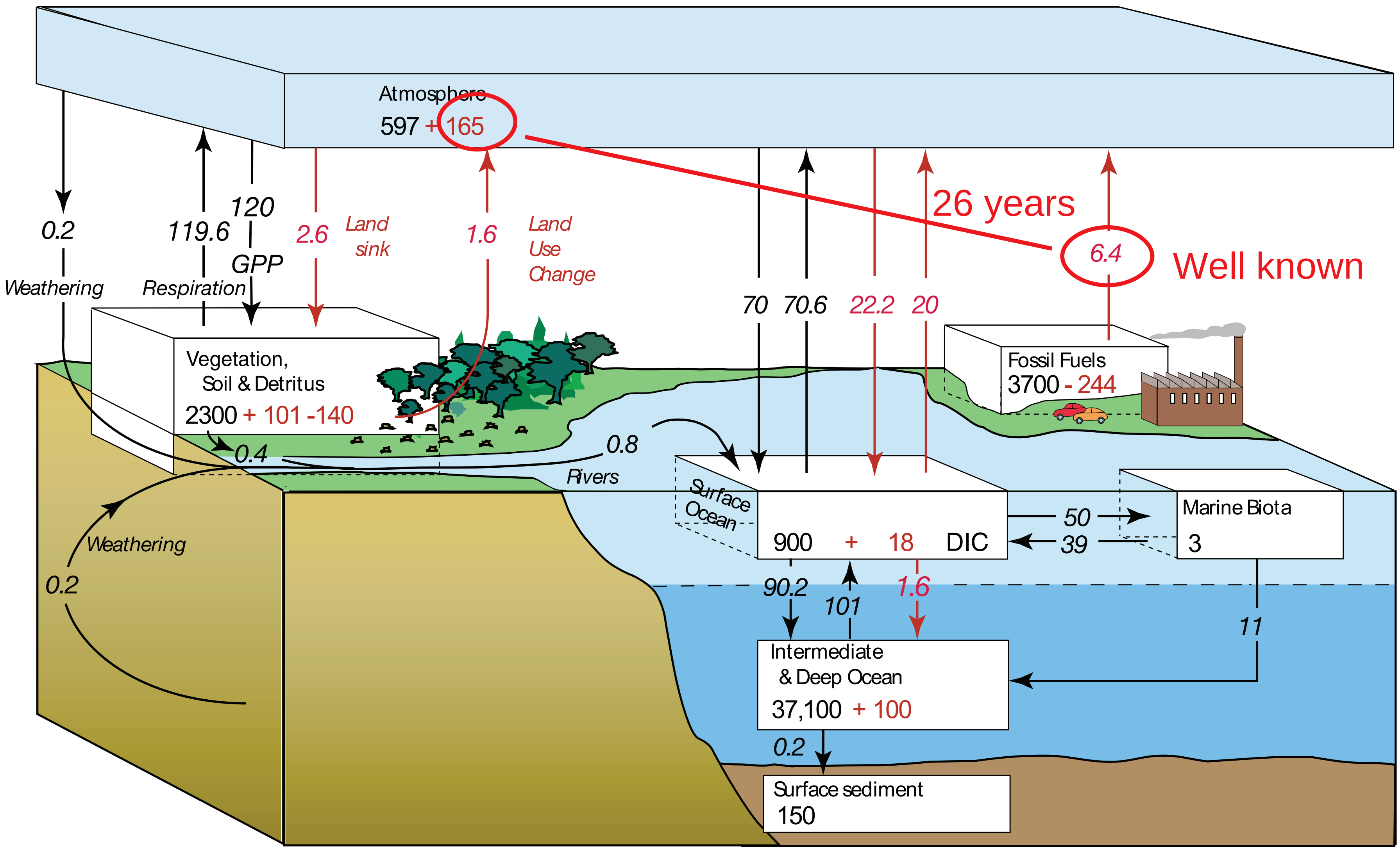
The question arises what time scale T one should use in this integration.


ATMOSPHERIC CARBON DIOXIDE IS INCREASING
380
360
340
320
300
280
260
240
220
200
180
CO_2 concentration (ppm)
370
360
350
340
330
320
310
1960
1970
1980
1990
2000
C. D. Keeling
Mauna Loa Hawaii
Law Dome
Adelie Land
Siple
South Pole
Polar ice cores
800
1000
1200
1400
1600
1800
2000
Year
Global carbon dioxide concentration over the last thousand years

THE GLOBAL CARBON CYCLE

Preindustrial and anthropogenic perturbation (1990's)

Stocks in upright type, Pg C; *flows in italic type,* Pg C yr^{-1}

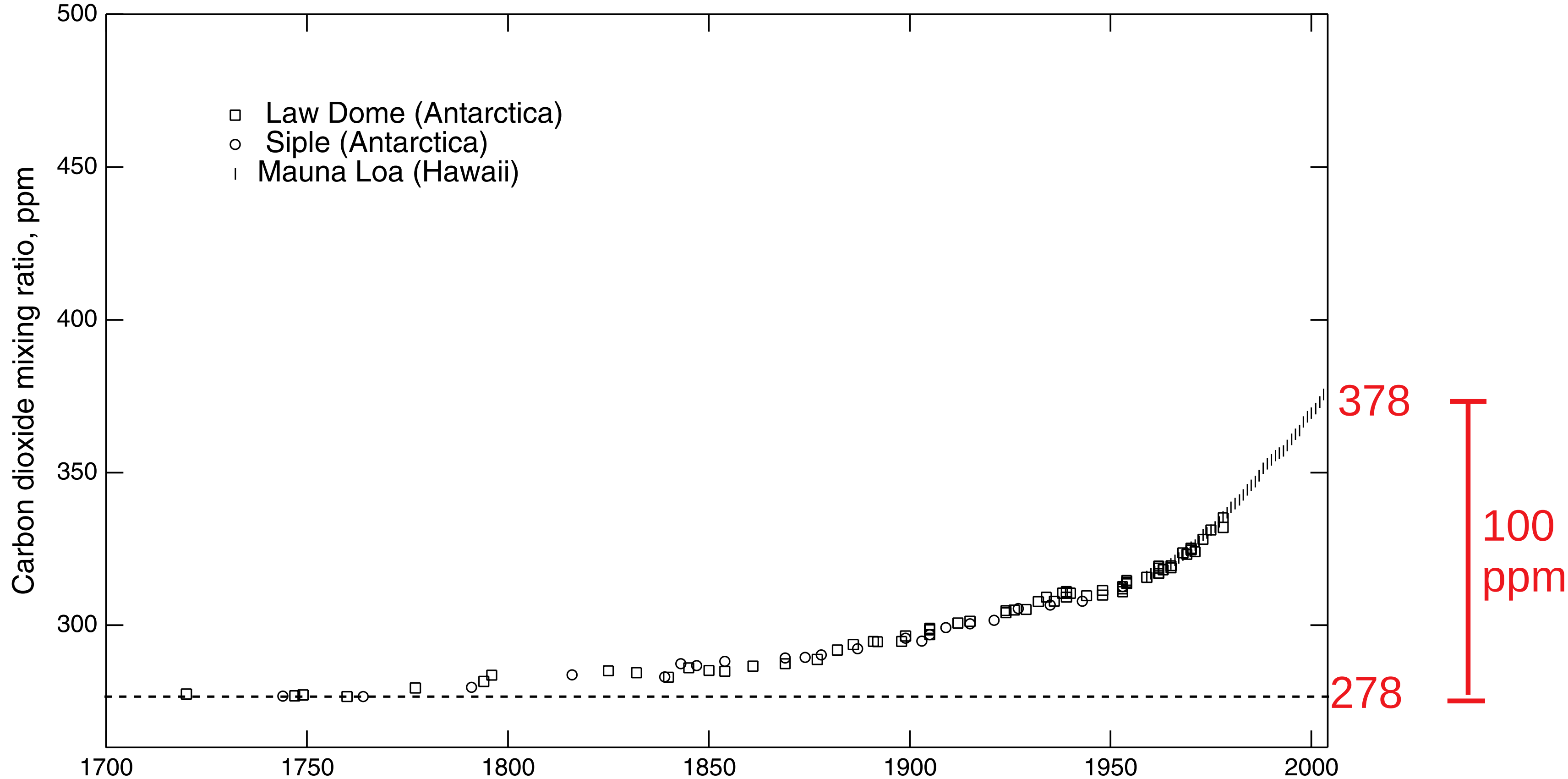


IPCC AR4, Chapter 7 (2007); after Sarmiento and Gruber (2002)

Excess atmospheric carbon dioxide is 26 years of current fossil fuel emissions.

ATMOSPHERIC CARBON DIOXIDE

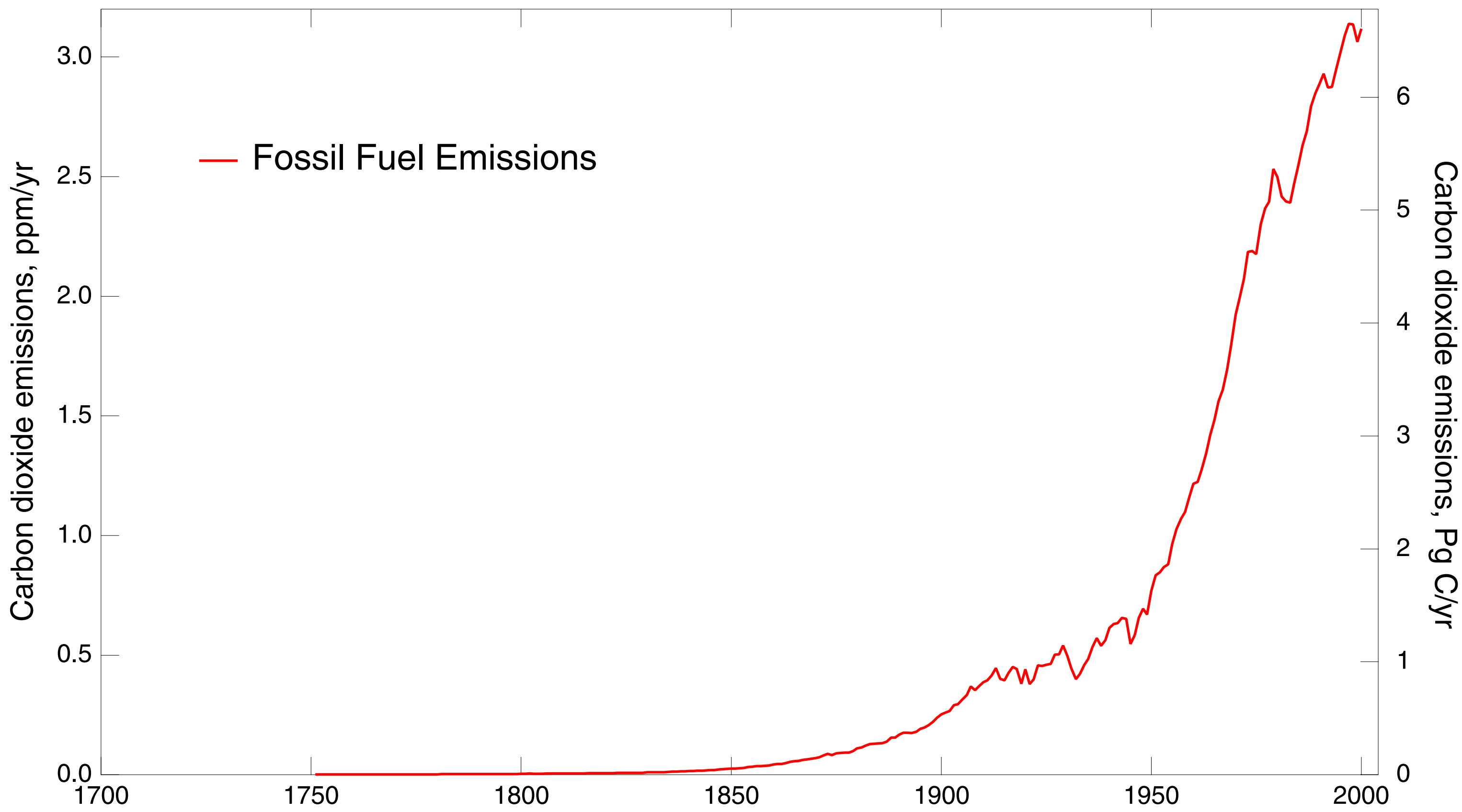
Time series 1700 - 2003



Law - Etheridge et al.
Siple - Friedli et al.
Mauna Loa - Keeling

FOSSIL FUEL CO_2 EMISSIONS

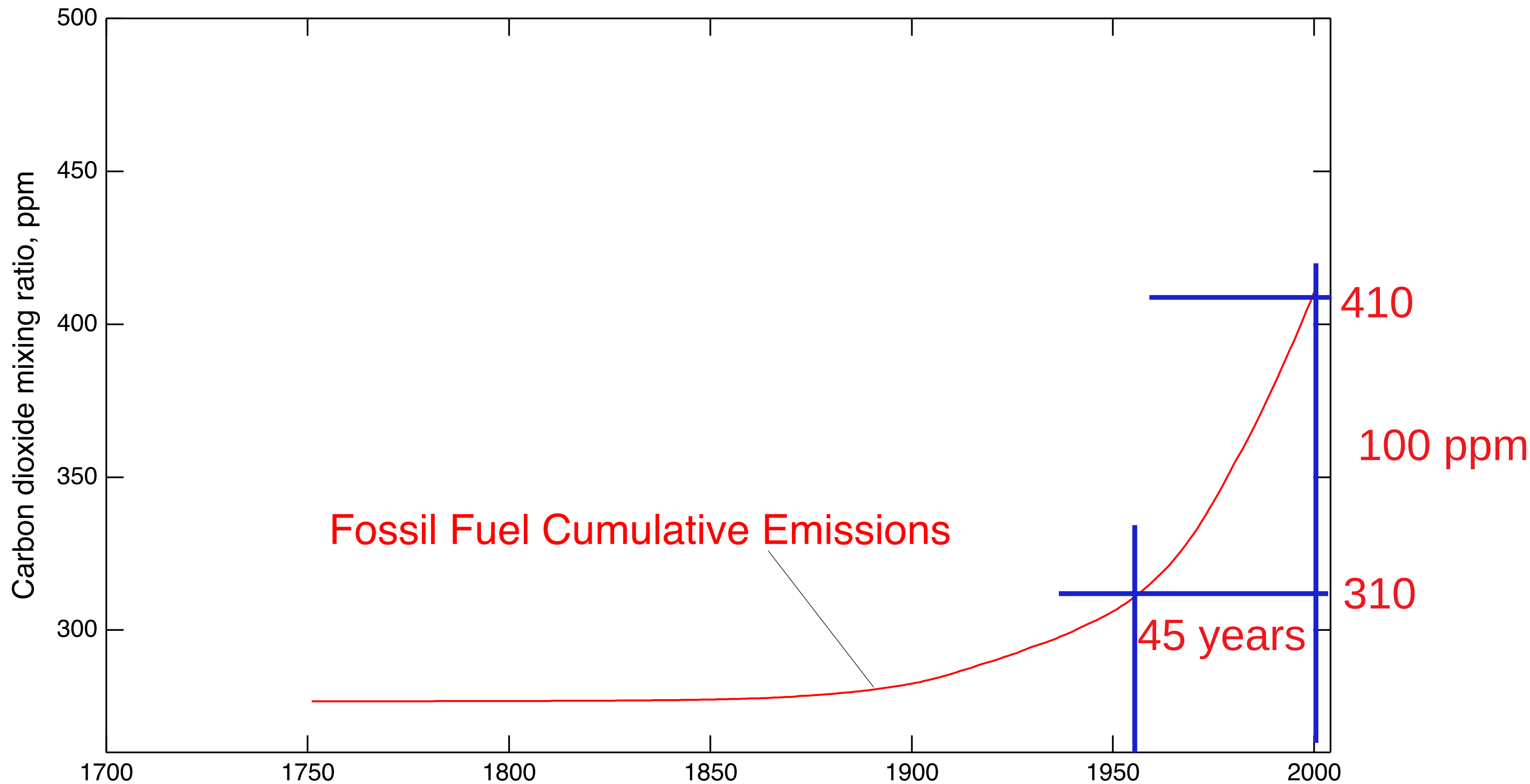
Time series 1700 - 2003



Fossil Fuel - Marland

FOSSIL CO_2 CUMULATIVE EMISSIONS

Time series 1700 - 2003



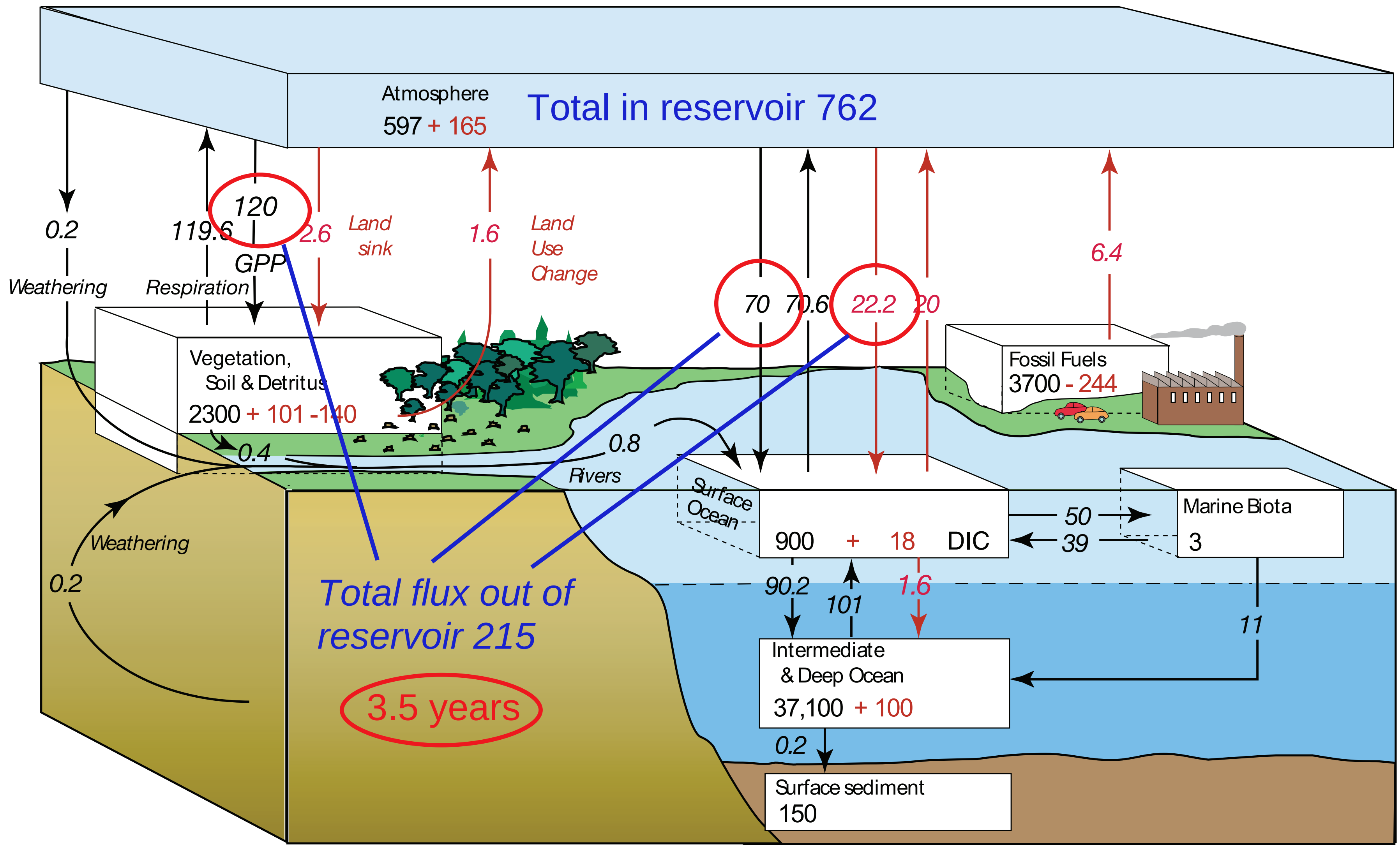
Fossil Fuel - Marland

Present excess CO_2 in the atmosphere is equal to 45 years of fossil fuel emissions.

THE GLOBAL CARBON CYCLE

Preindustrial and anthropogenic perturbation (1990's)

Stocks in upright type, Pg C; *flows in italic type,* Pg C yr^{-1}



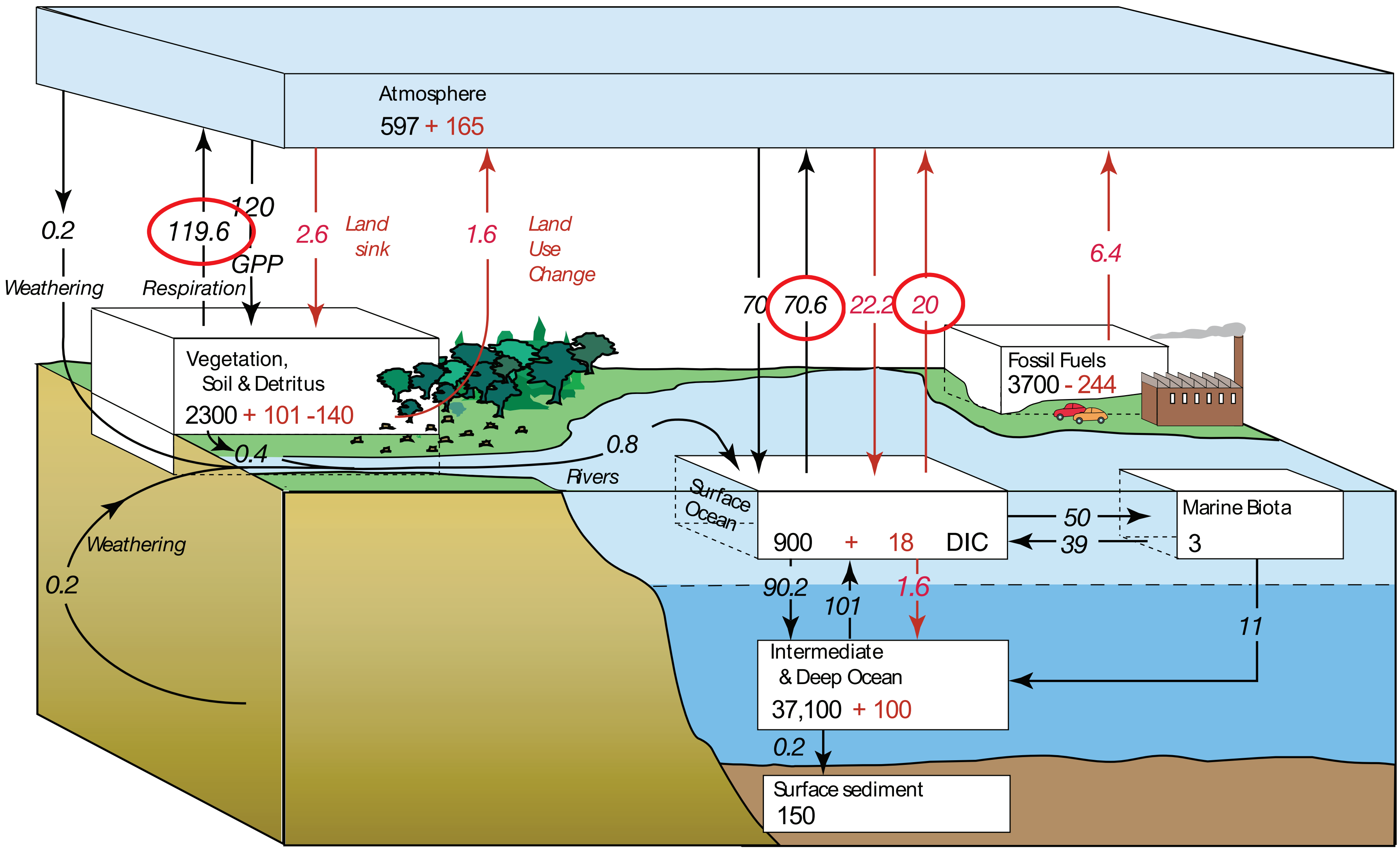
IPCC AR4, Chapter 7 (2007); after Sarmiento and Gruber (2002)

Large fluxes out of atmosphere suggest much shorter lifetime ~ 3.5 yr.

THE GLOBAL CARBON CYCLE

Preindustrial and anthropogenic perturbation (1990's)

Stocks in upright type, Pg C; *flows in italic type,* Pg C yr^{-1}



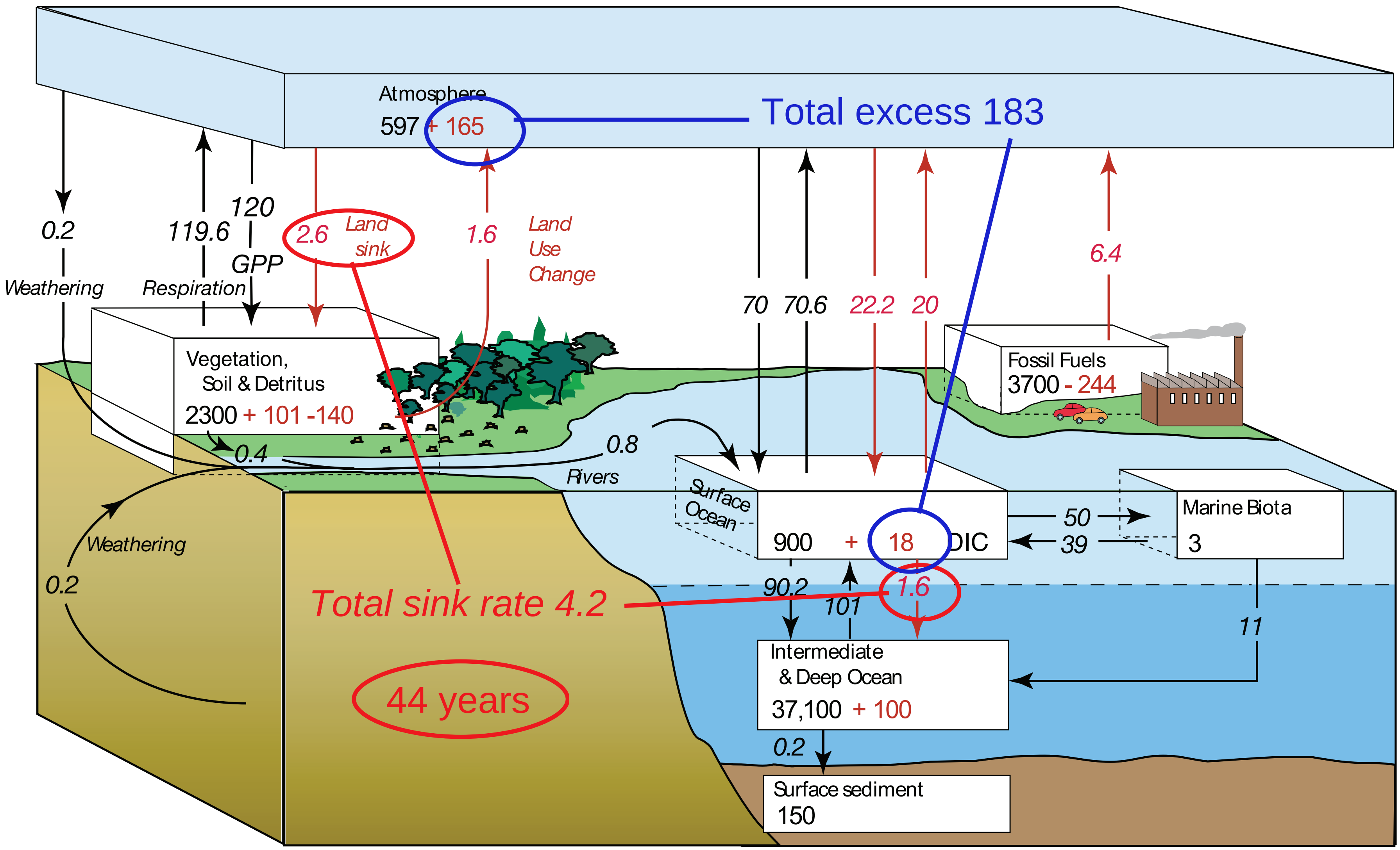
IPCC AR4, Chapter 7 (2007); after Sarmiento and Gruber (2002)

Paradox resolved: Large return flux indicates coupled reservoirs.

THE GLOBAL CARBON CYCLE

Preindustrial and anthropogenic perturbation (1990's)

Stocks in upright type, Pg C; *flows in italic type,* Pg C yr^{-1}

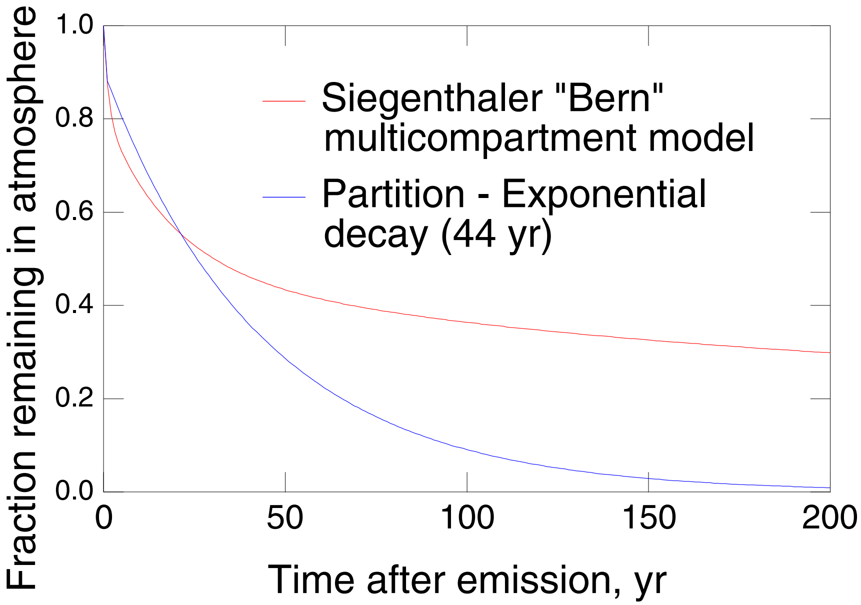


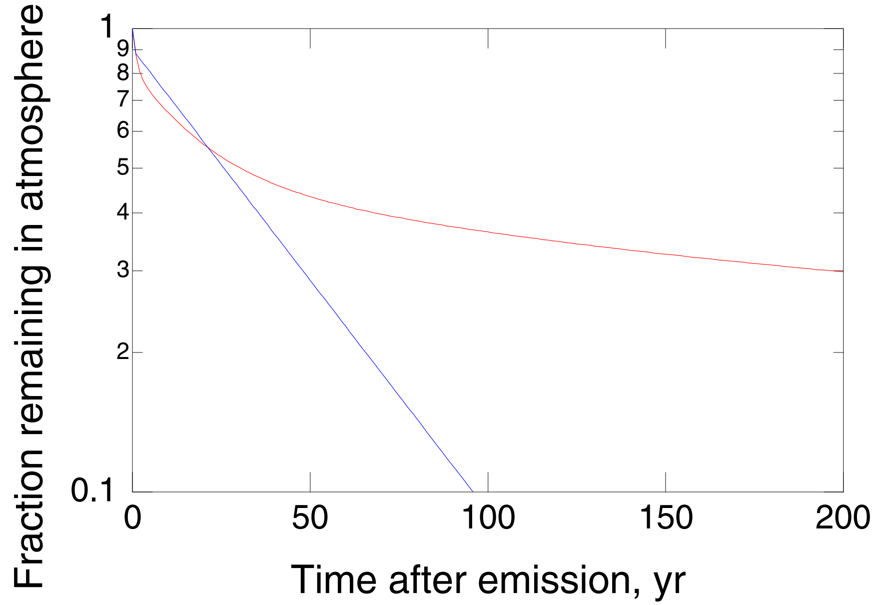
IPCC AR4, Chapter 7 (2007); after Sarmiento and Gruber (2002)

Turnover time calculated as (excess C)/(sink rate) is 44 yr.

ALTERNATE VIEWS OF THE CO_2 IMPULSE RESPONSE FUNCTION

Comparison on linear and semilogarithmic plots



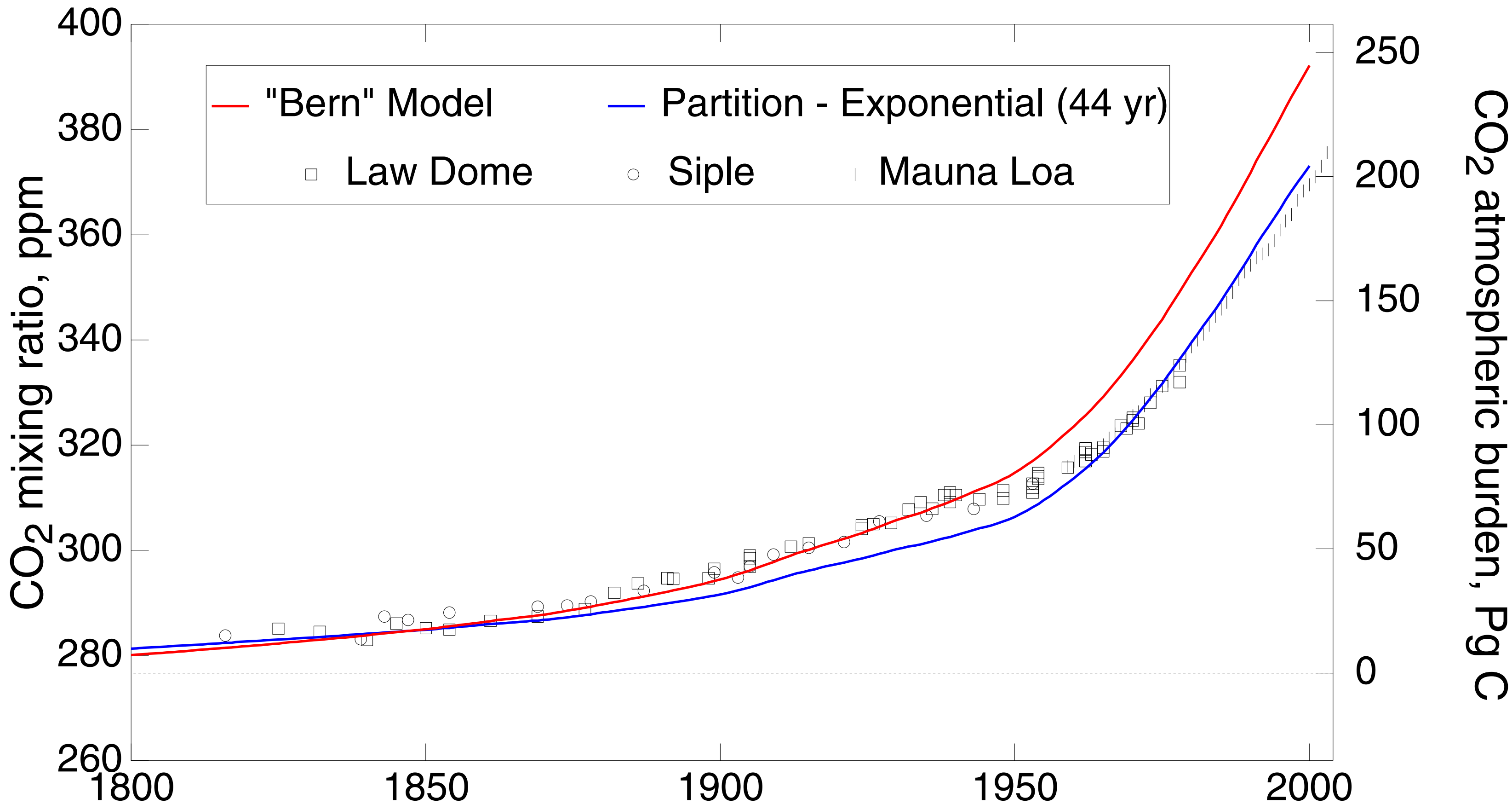


Bern model is basis for assertions that excess CO_2 is long lived in the atmosphere.

Response functions closely agree over initial 30 years but diverge greatly at long times.

COMPARISON OF MODELED AND OBSERVED CO_2 MIXING RATIO

Fossil emissions from Marland; land-use emissions from Houghton



Both models reproduce observations given uncertainties in emissions.

Long term impulse response is irrelevant for rapidly increasing emissions.

Knowledge of the true impulse response is essential to energy planning.

CHARACTERISTIC TIME OF EARTH'S CLIMATE SYSTEM

I add a watt per square meter to Earth's energy budget, and then

Earth warms up: Can you tell me when?

Incremental heating "in the pipeline" from excess CO_2 already in the atmosphere

Earth's climate sensitivity

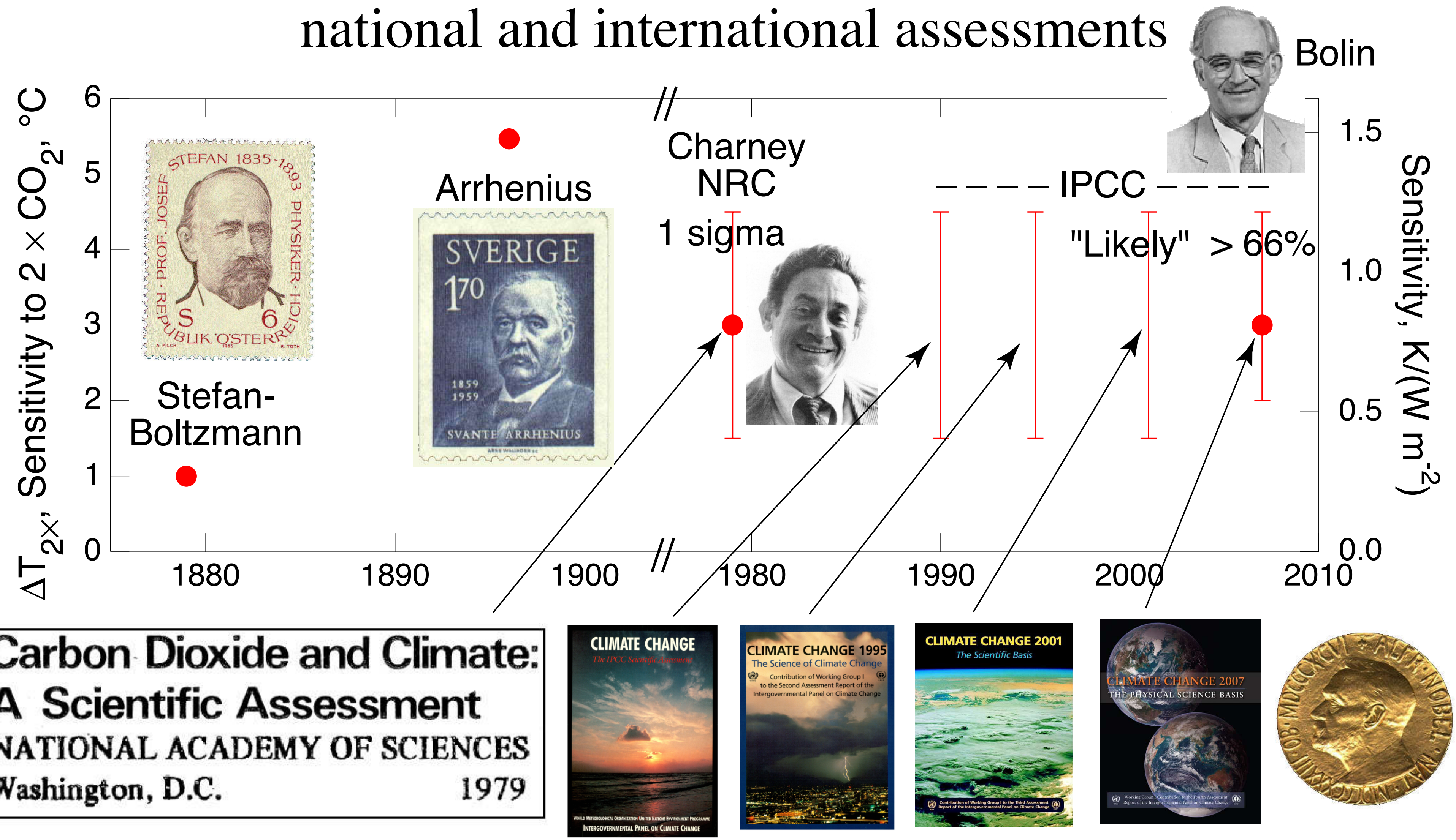
APPROACH TO DETERMINE EARTH'S CLIMATE SENSITIVITY

Empirically determine heat capacity C and time constant τ of Earth's climate system from measurements over the instrumental period.

Evaluate sensitivity as $\lambda^{-1} = \tau/C$

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments



Despite extensive research, climate sensitivity remains ***highly uncertain***.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $C\frac{dT_s}{dt} = \frac{dH}{dt} = Q - E = \gamma J - \varepsilon\sigma T_s^4$

C is heat capacity coupled to climate system on relevant time scale

T_s is global mean surface temperature

H is global heat content

Q is absorbed solar energy

E is emitted longwave flux

J is $\frac{1}{4}$ solar constant

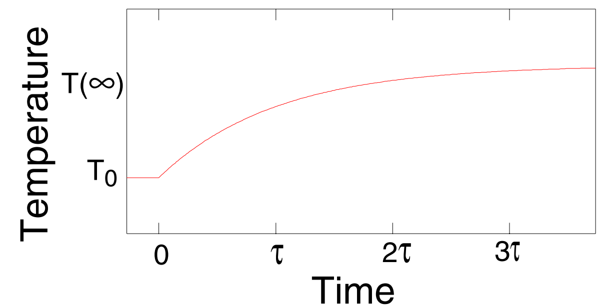
γ is planetary co-albedo

σ is Stefan-Boltzmann constant

ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Apply step-function forcing: $F = \Delta(Q - E)$



At "equilibrium" $\Delta T_S(\infty) = \lambda^{-1} F$

λ^{-1} is equilibrium climate sensitivity Units: K / (W m^{-2})

Time-dependence: $\Delta T_S(t) = \lambda^{-1} F (1 - e^{-t/\tau})$

τ is climate system time constant $\lambda^{-1} = \tau / C$

One equation in three unknowns!

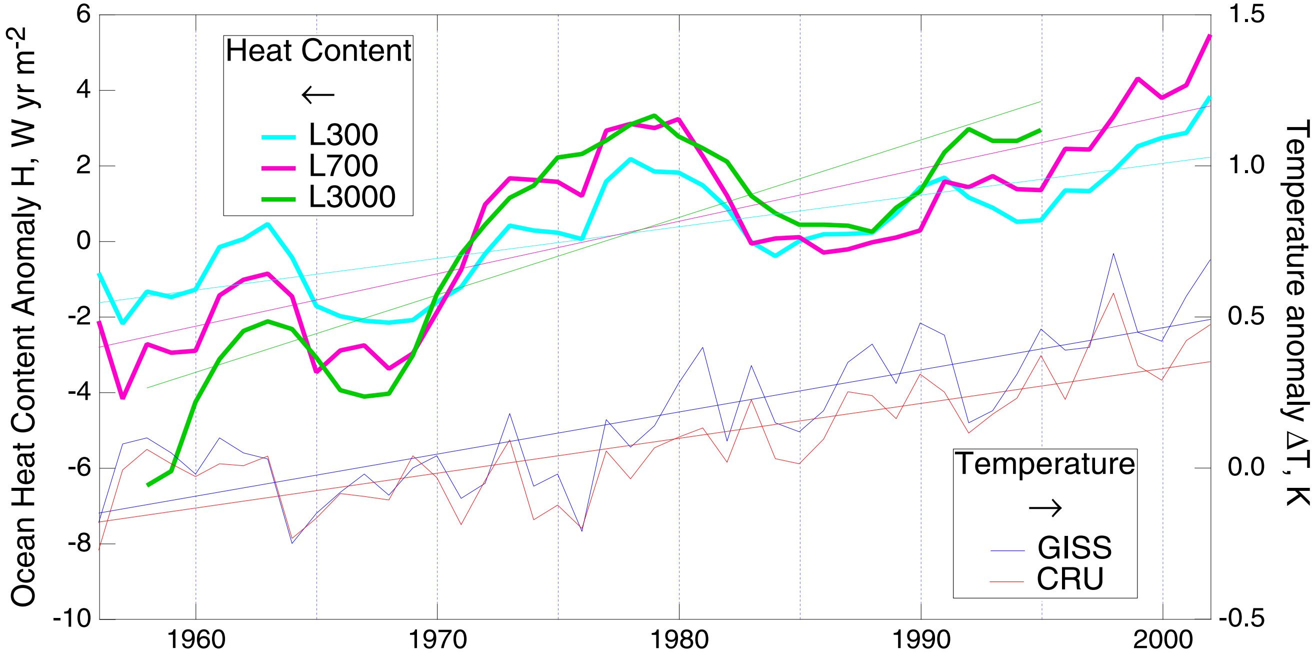
Approach: Determine C and τ empirically; calculate sensitivity λ^{-1}.

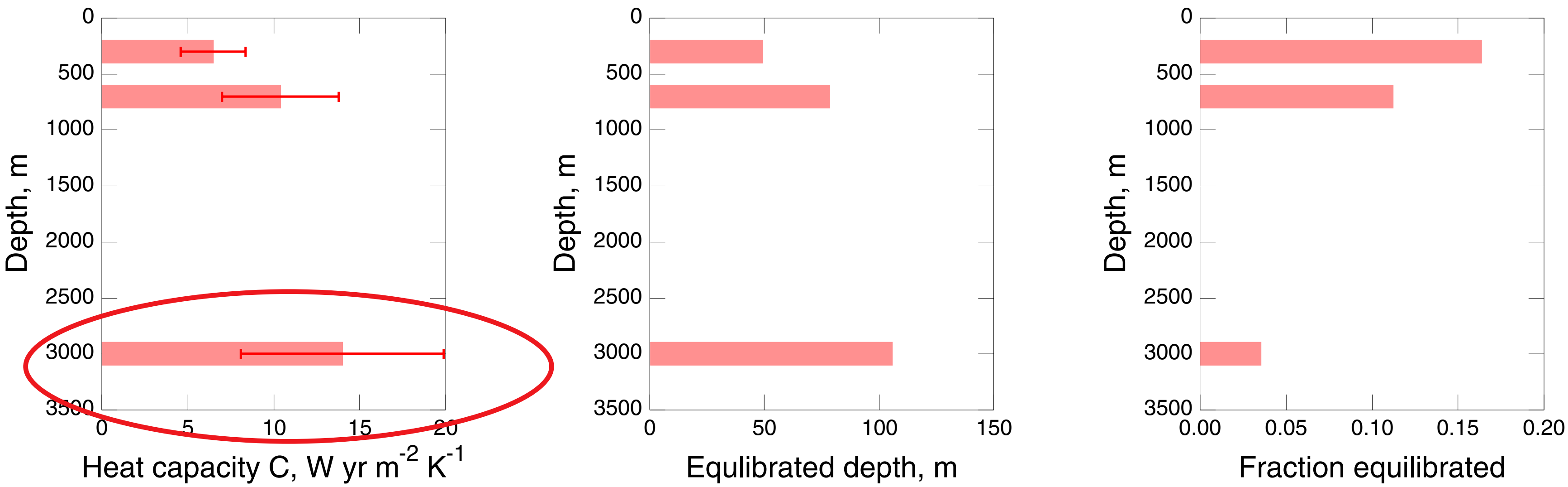
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

$$C = \frac{dH / dt}{dT_S / dt}$$

Ocean heat content *H*: Levitus *et al.*, GRL, 2005

Surface temperature T_S: GISS, CRU



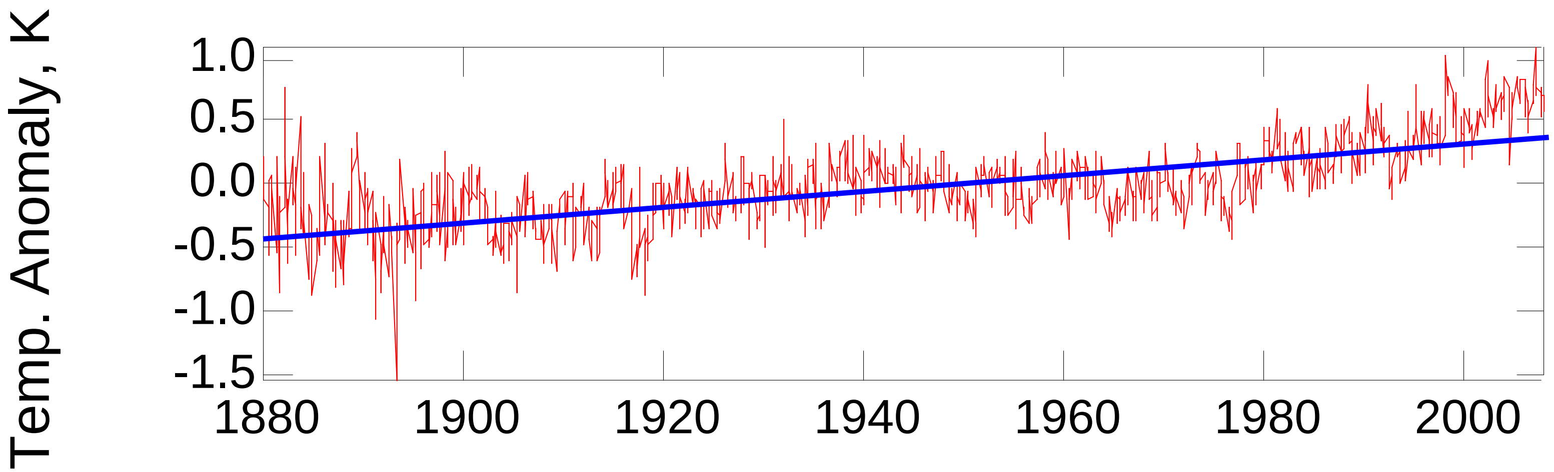


- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

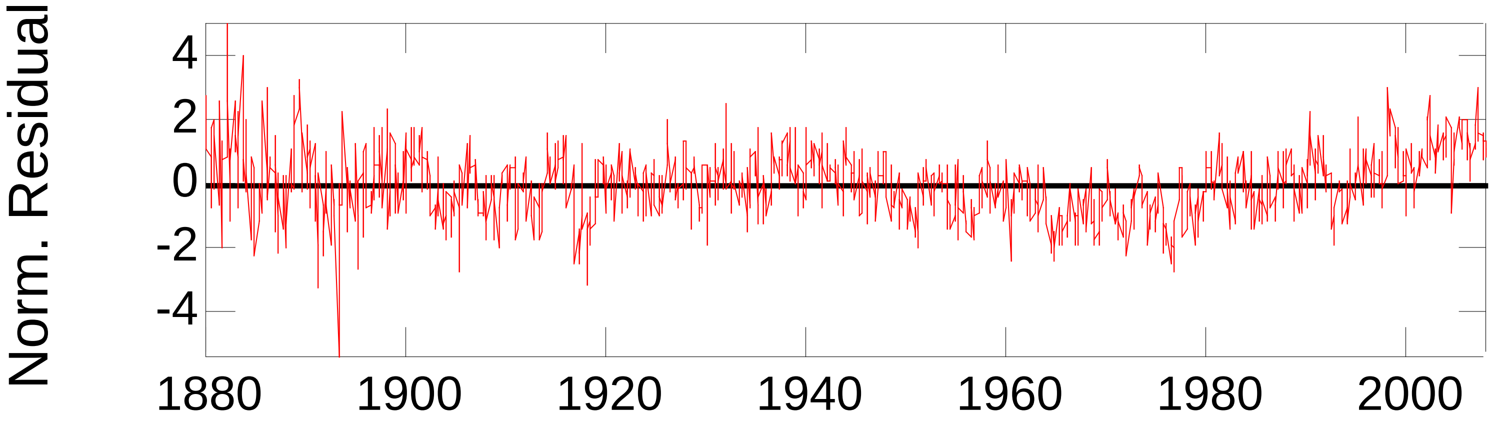
Schwartz, JGR, 2007

TIME CONSTANT OF EARTH'S CLIMATE SYSTEM
Determination from autocorrelation of time series

Input: Monthly global-mean surface temperature anomaly T_s



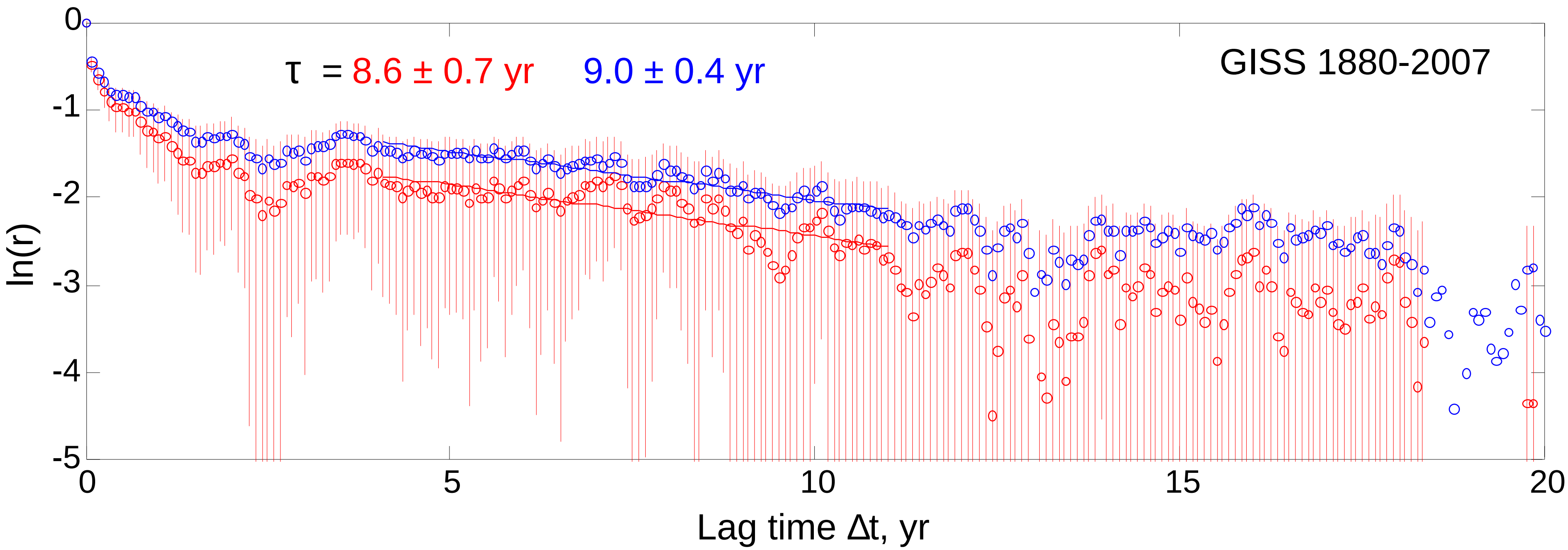
Remove long term trend; plot the residuals:



TIME CONSTANT OF EARTH'S CLIMATE SYSTEM
Determination from autocorrelation of time series (*cont'd*)

Evaluate ***climate system time constant*** as $\tau = (d \ln r(\Delta t)/d\,\Delta t)^{-1}$

Correct for short duration of time series.



Summary (multiple data sets):

Climate system time constant is 8.5 ± 2.5 years

Schwartz, JGR, in press, 2008

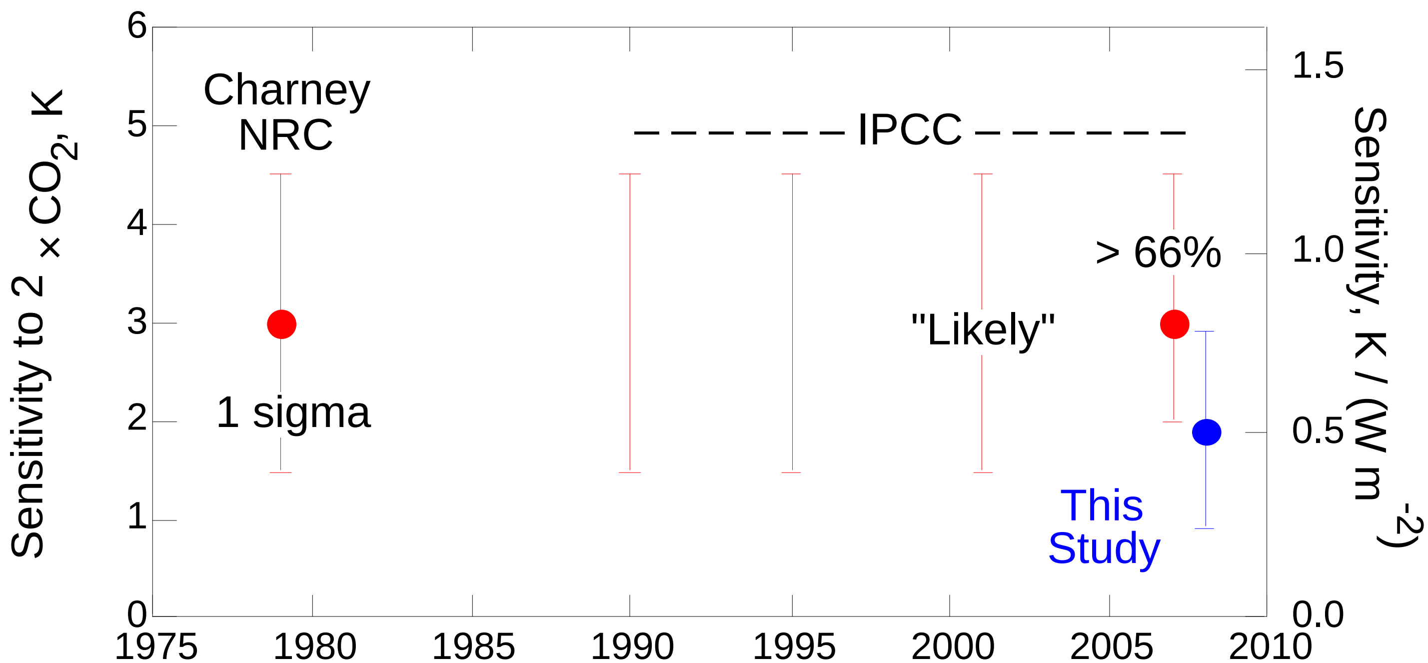
IMPLICATIONS

Climate system time constant is 8.5 ± 2.5 years.

Short time constant implies ***little further heating "in the pipeline"*** from present greenhouse gases.

Earth's ***climate sensitivity*** is 0.51 ± 0.26 K /(W m^{-2}).

CO_2 *doubling temperature* $\Delta T_{2\times}$ = 1.9 ± 1.0 K.



IT'S ABOUT TIME

THANK YOU, HENNING