LIFETIME OF ANTHROPOGENIC CO_2

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OUR COLLECTIVE ENERGY USE

Standard diet US adult: 2000 Calories (k cal) per day

Equivalent to 100 watts

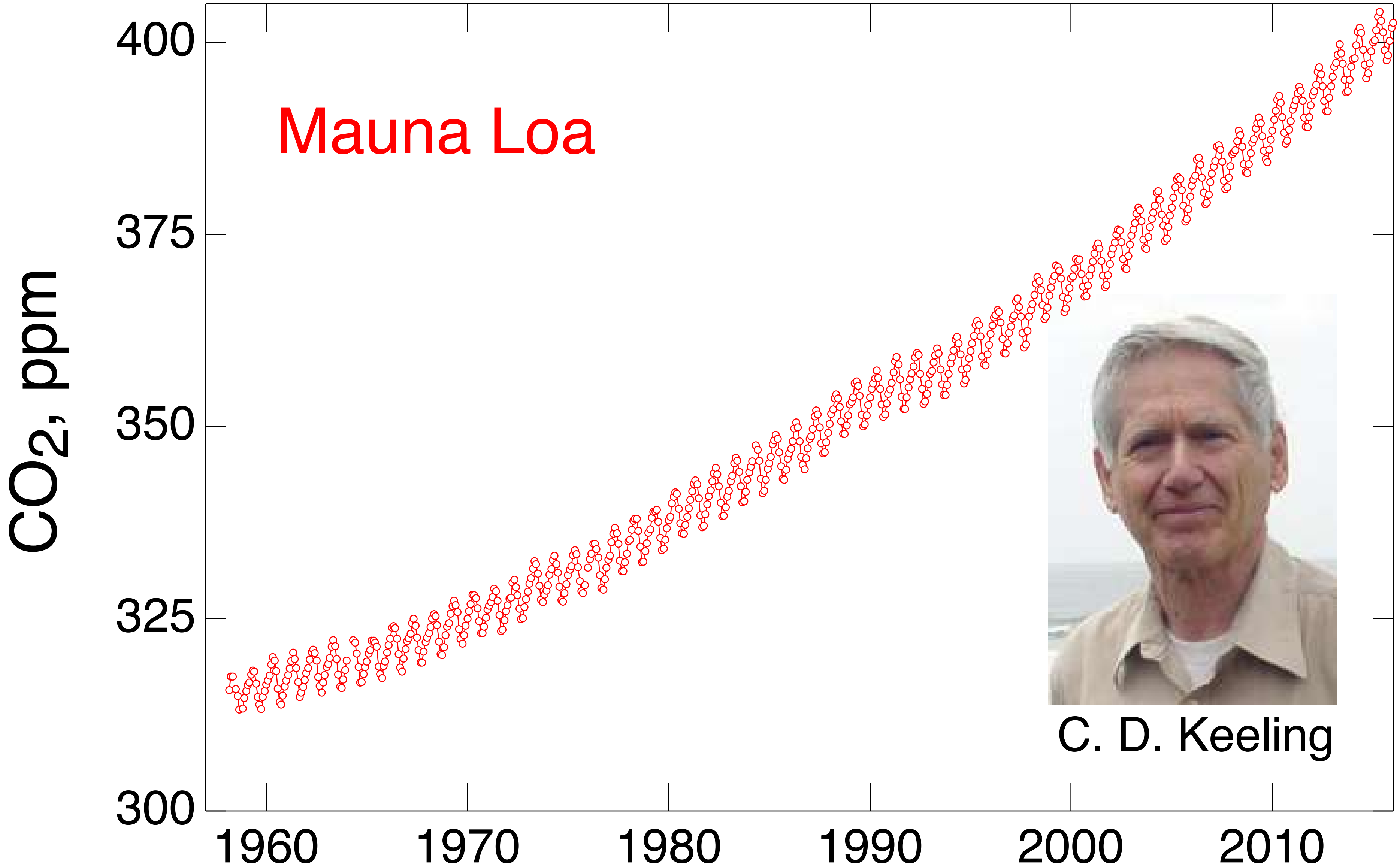
Per capita energy US use: 10,000 watts

100 100-watt light bulbs, 24 – 7

Equivalent to 100 people!

And all these “people” are exhaling CO_2!

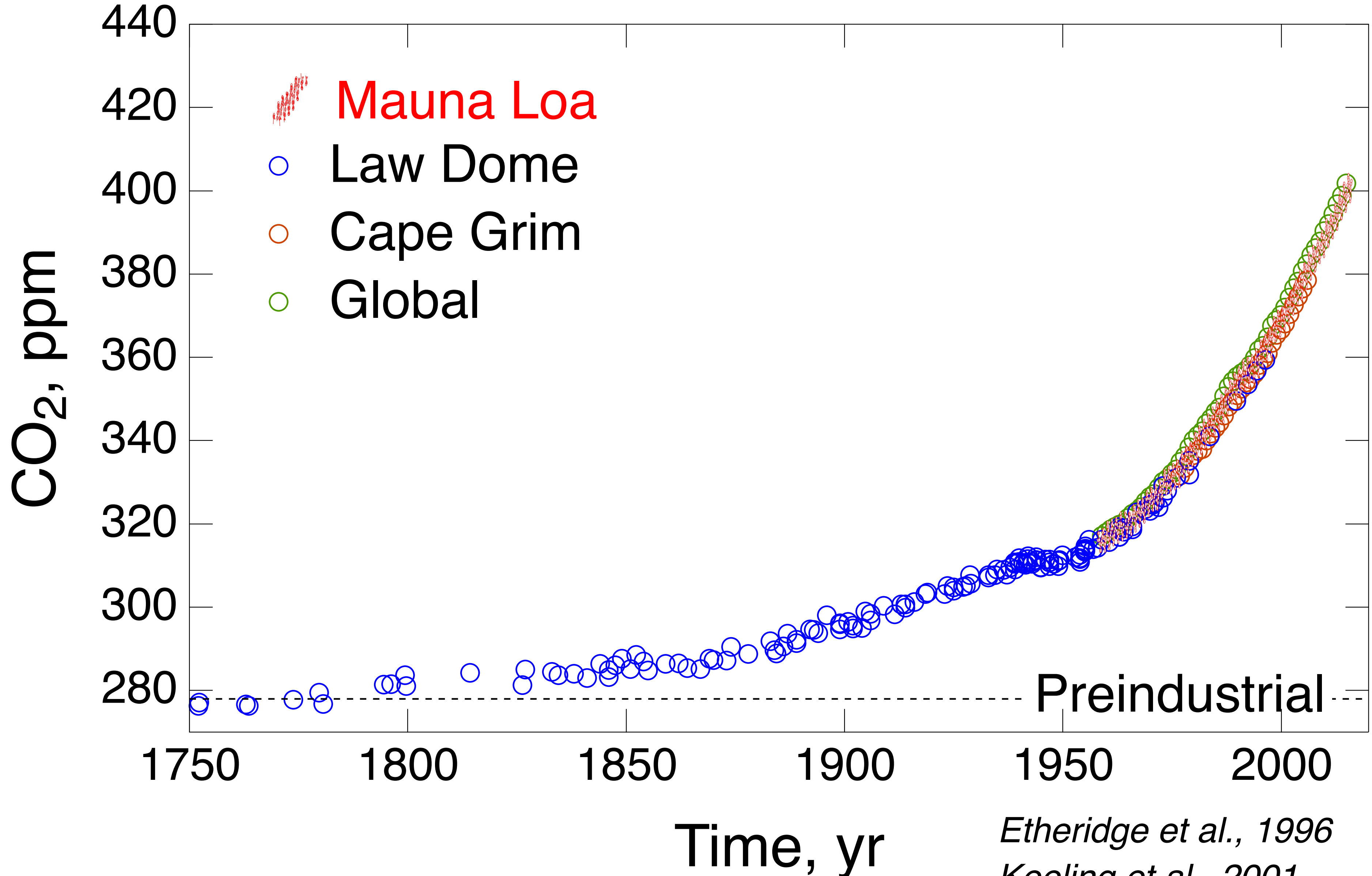
THE KEELING CURVE



Atmospheric CO_2 has increased substantially over this period.

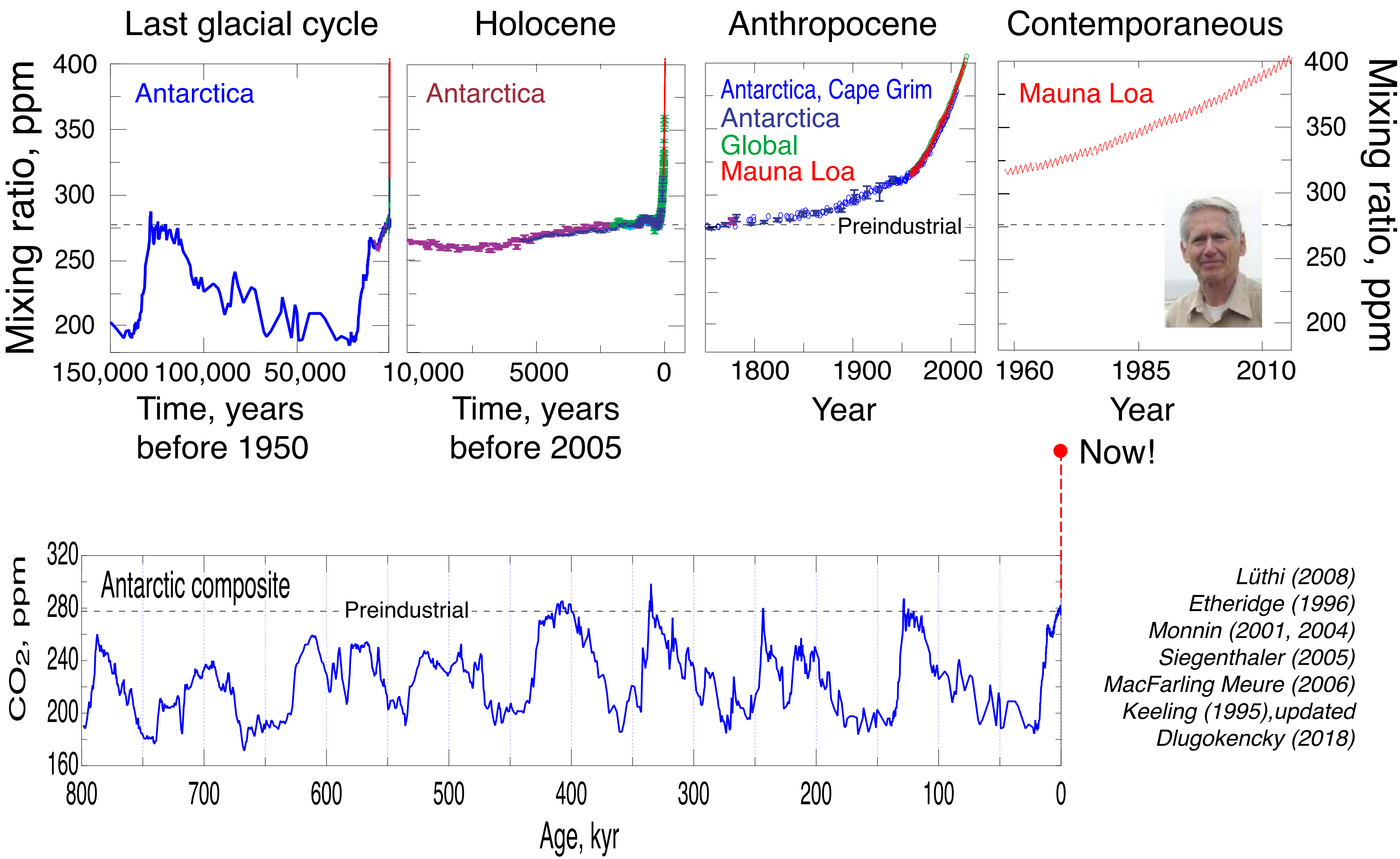
Annual cycle of monthly means is due to drawdown and release from the terrestrial biosphere.

CARBON DIOXIDE OVER THE ANTHROPOCENE



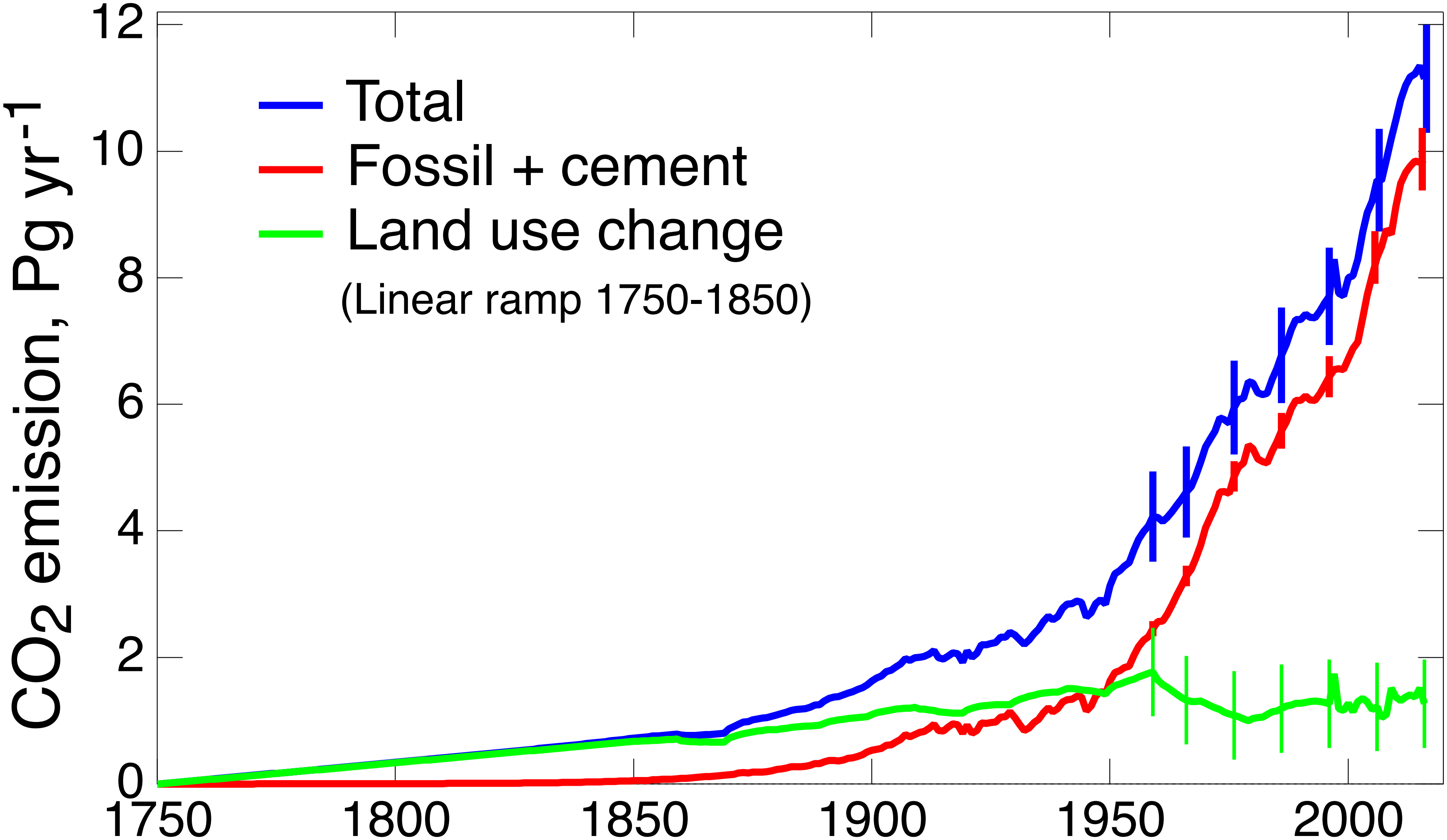
Etheridge et al., 1996
Keeling et al., 2001
Duglokencky &Tans, 2018

CARBON DIOXIDE OVER TIME



Lüthi (2008)
Etheridge (1996)
Monnin (2001, 2004)
Siegenthaler (2005)
MacFarling Meure (2006)
Keeling (1995),updated
Dlugokencky (2018)

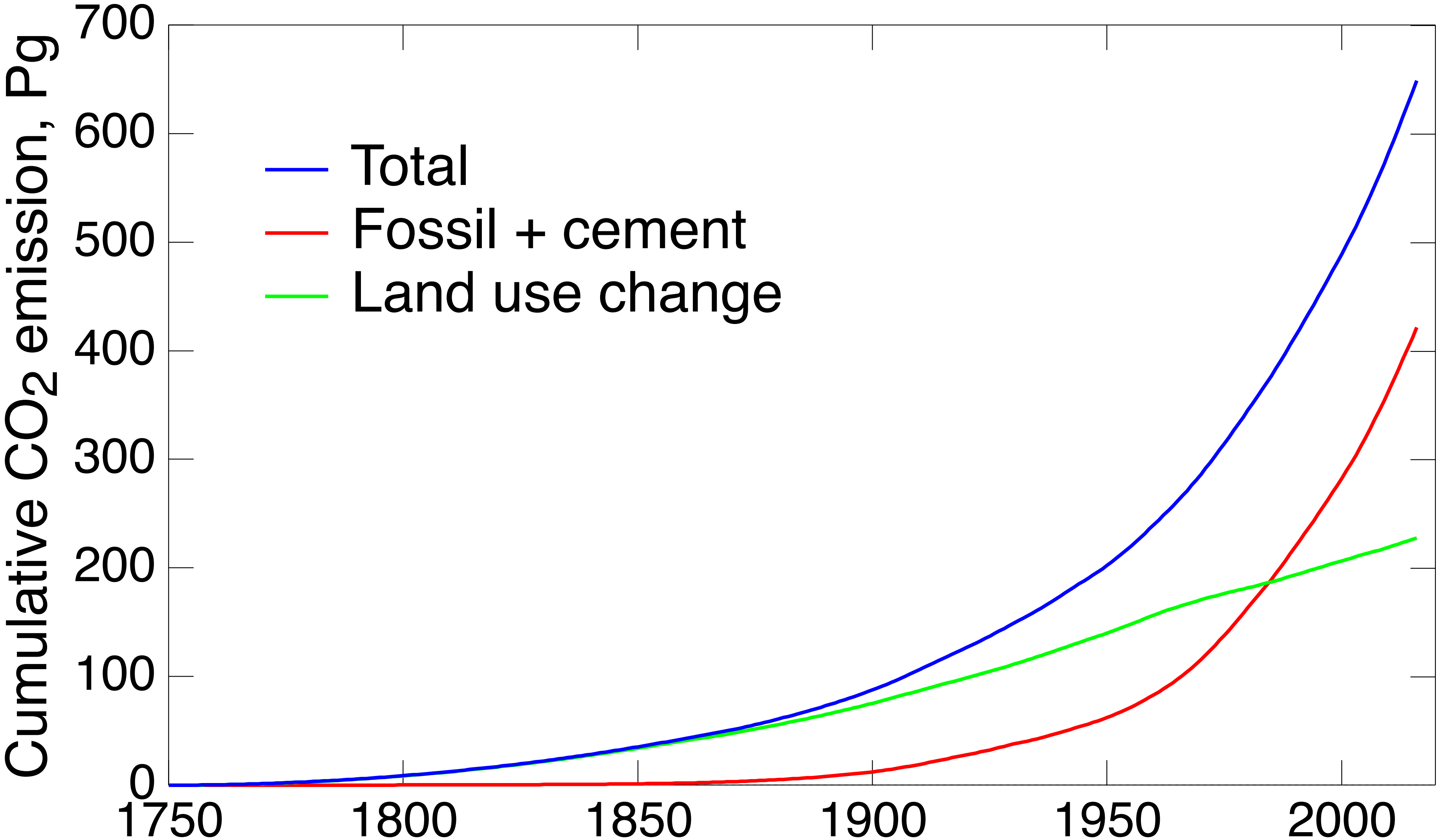
ANTHROPOGENIC CARBON DIOXIDE EMISSIONS



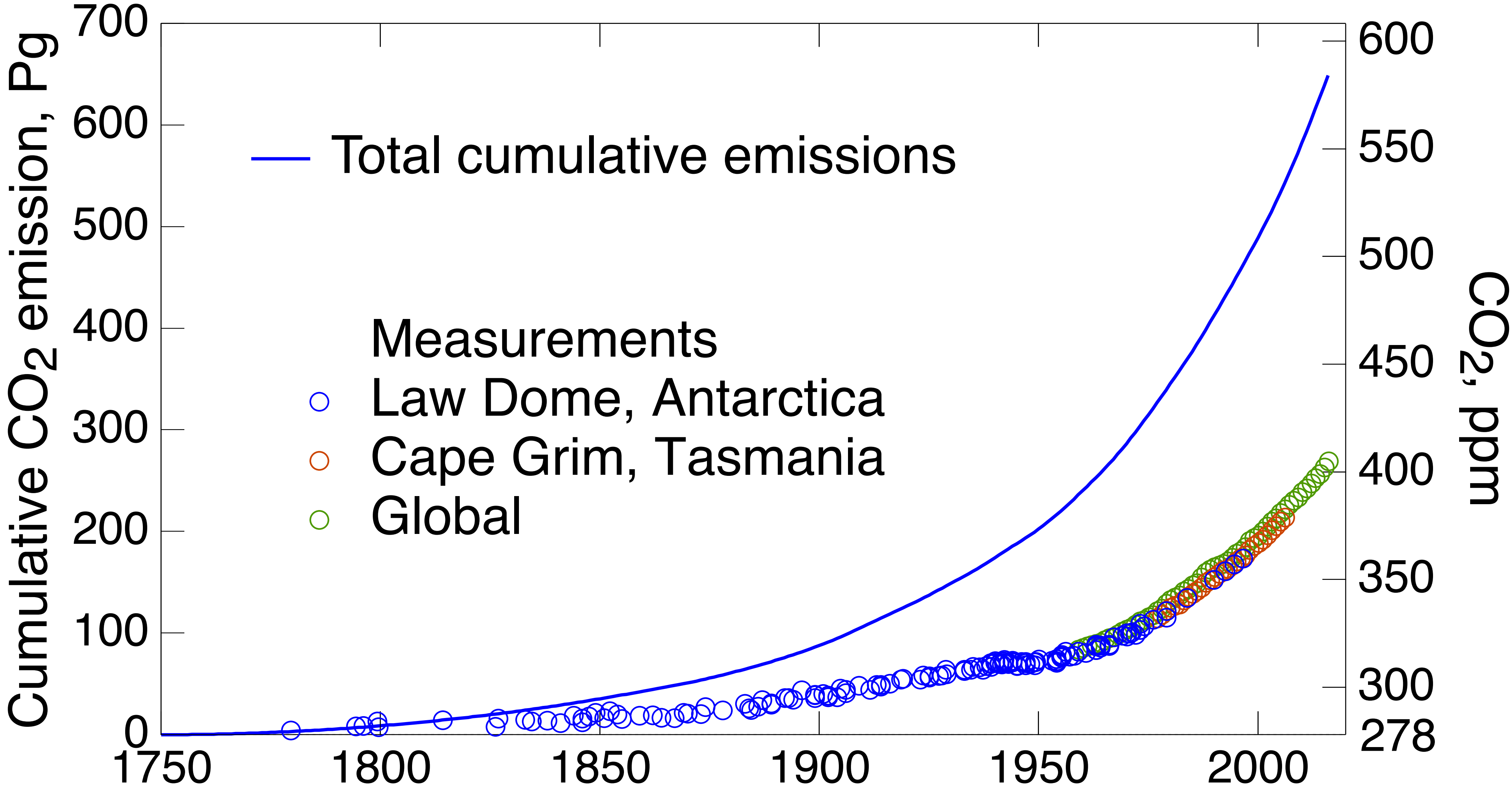
Boden et al., 2017

Houghton and Nassikas, 2017

CUMULATIVE ANTHROPOGENIC CO_2 EMISSIONS



CUMULATIVE ANTHROPOGENIC CO_2 EMISSIONS AND ANTHROPOGENIC ATMOSPHERIC STOCK



Nature's "subsidy" of our carbon dioxide emissions

Motivation for this study

(How did I get interested in this question?)

Long interest in aerosol radiative influences on climate change

Questions of what would (or will) happen as combustion of fossil fuels is decreased

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2017JD028121

2018

Unrealized Global Temperature Increase: Implications of Current Uncertainties

Stephen E. Schwartz

The “Cold Turkey” Experiment

Abrupt cessation Of emissions

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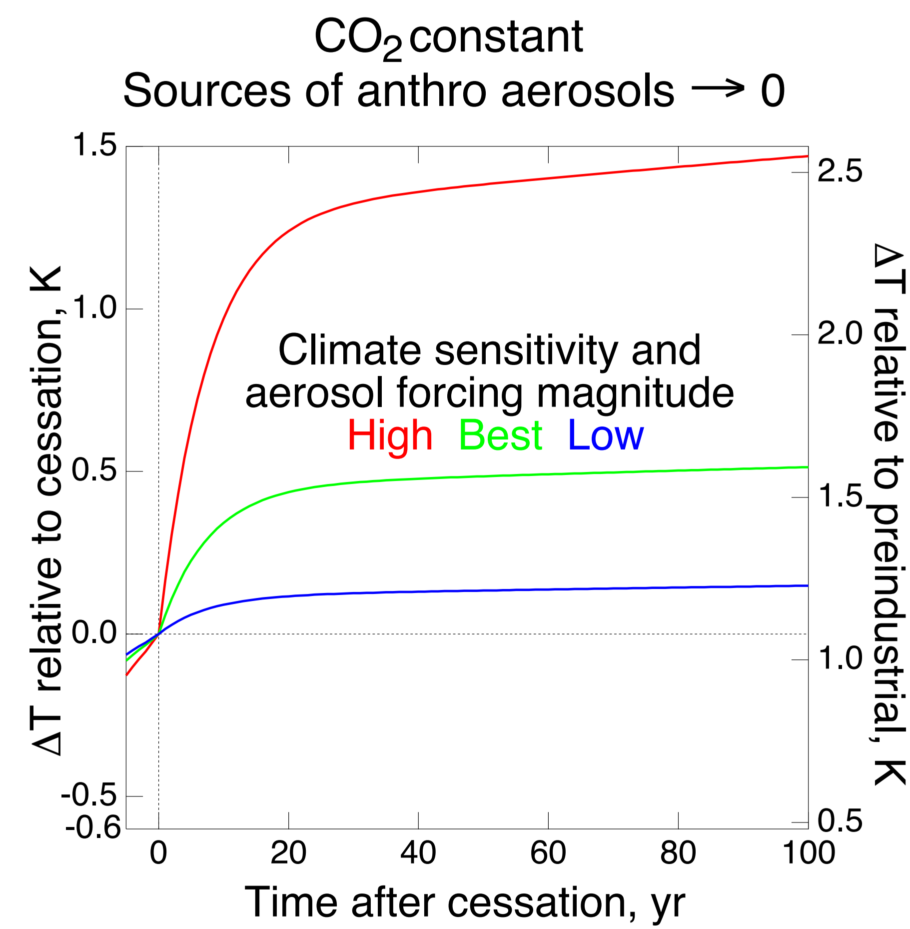
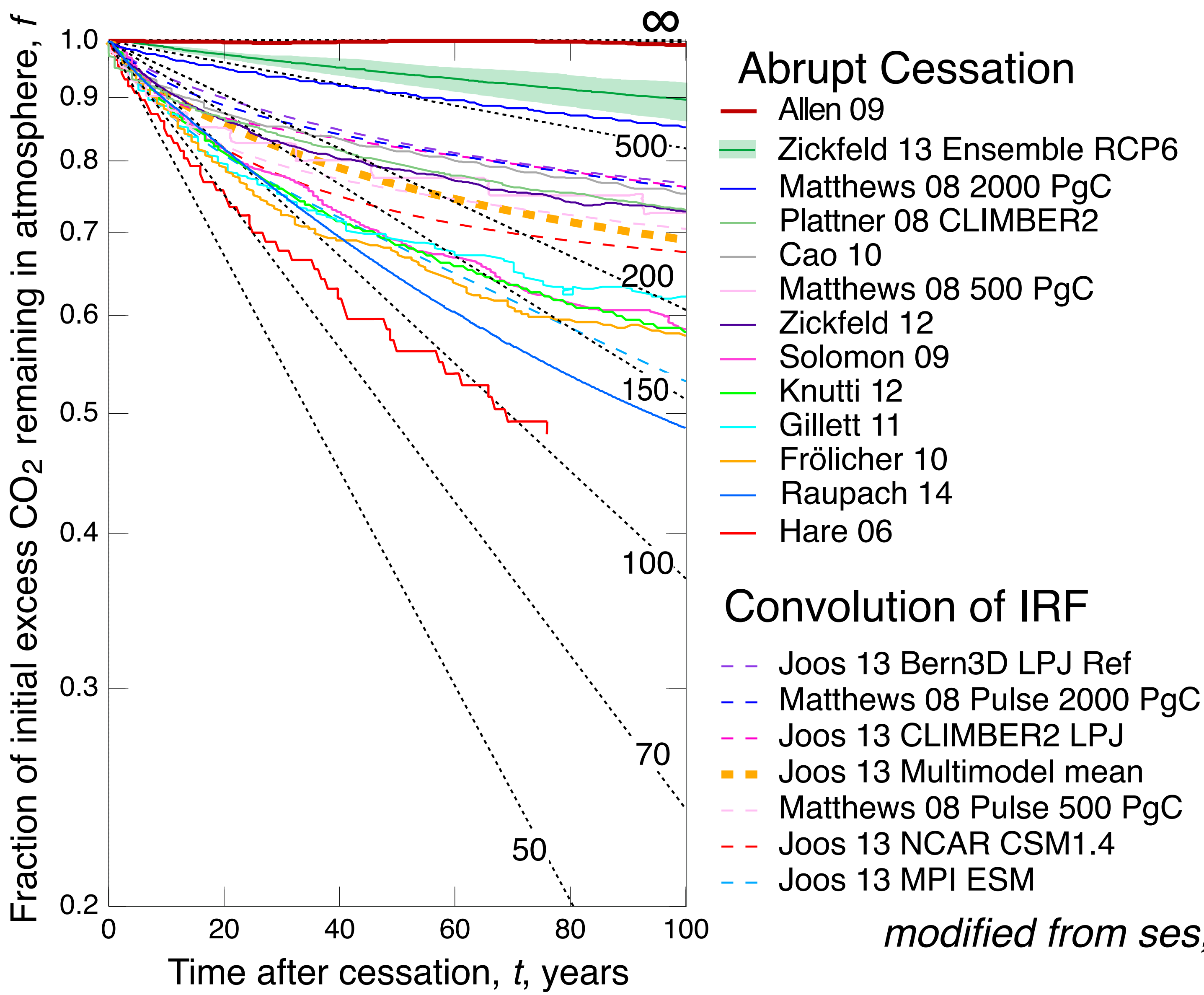


DECAY OF EXCESS ATMOSPHERIC CO_2 AFTER ABRUPT CESSATION OF EMISSIONS

Calculated and redrawn from recent publications



modified from ses, jgr, 18

Current estimates vary by an ***order of magnitude!***

AGU PUBLICATIONS

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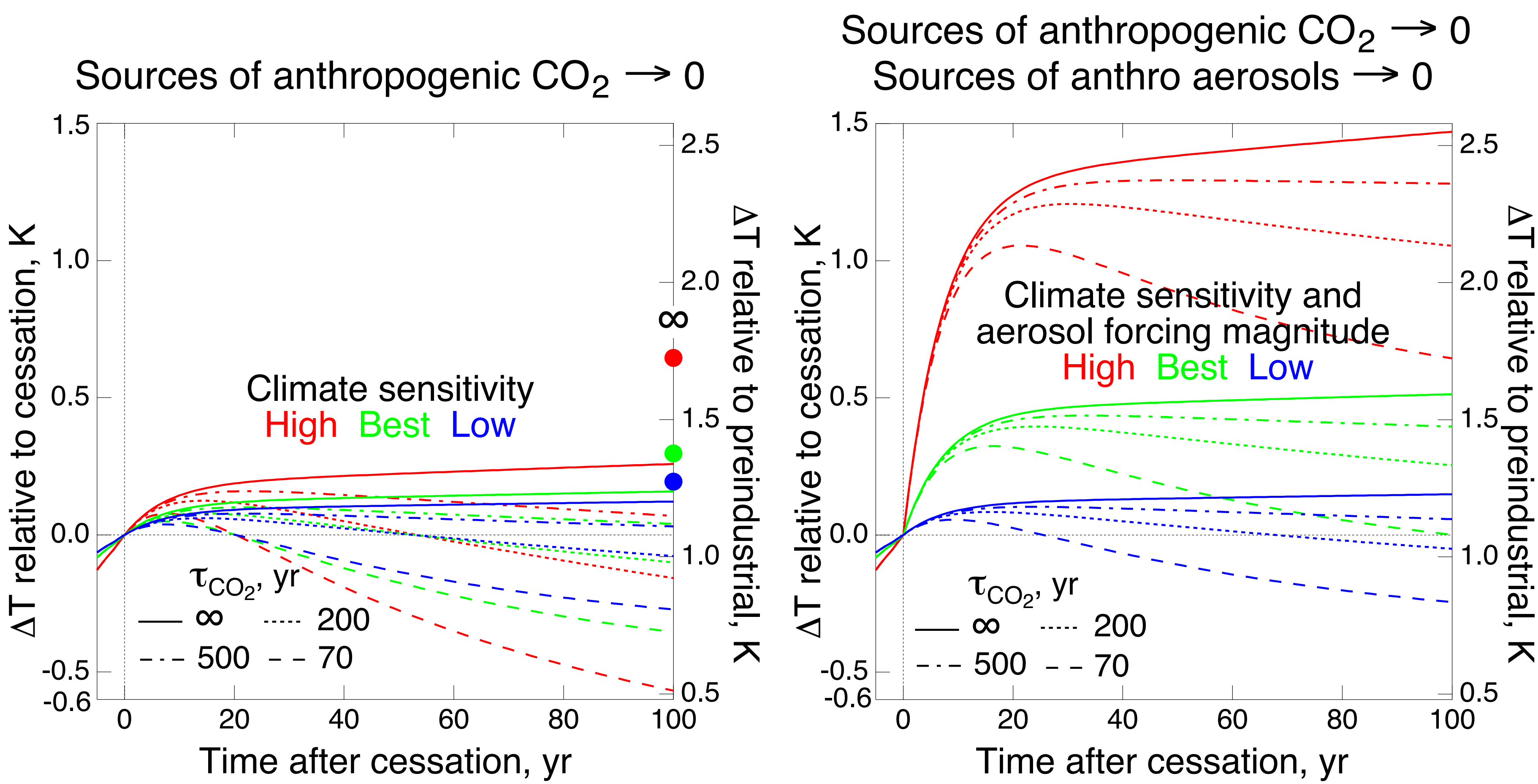

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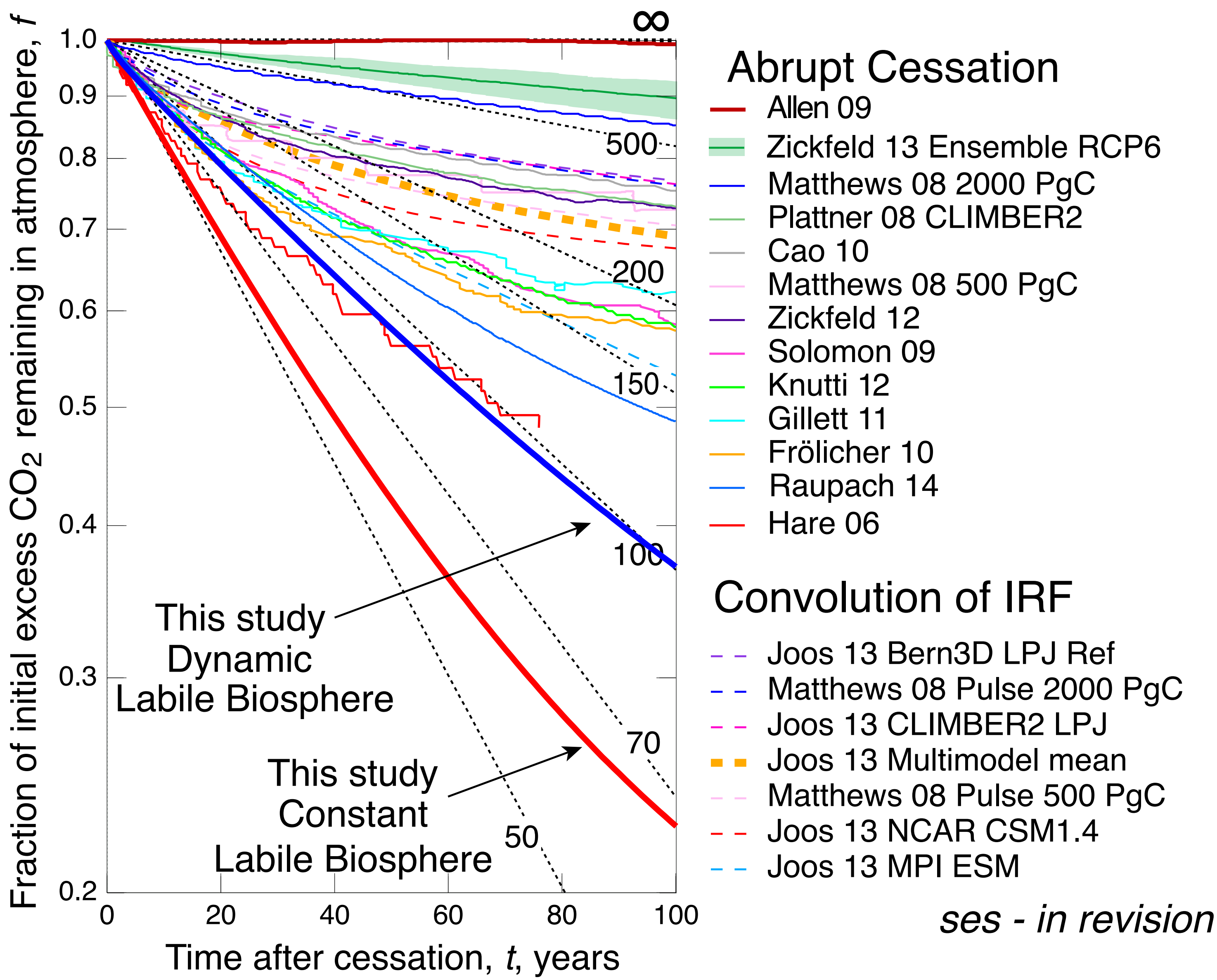


ses - in revision

Lifetime (60 – 100 yr) is ***much shorter than in prior studies.***

Lifetime

How is it defined?

How is it determined?

Annual Review of Earth and Planetary Sciences 2009

Atmospheric Lifetime of Fossil Fuel Carbon Dioxide

David Archer, Michael Eby, Victor Brovkin, Andy Ridgwell, Long Cao, Uwe Mikolajewicz, Ken Caldeira, Katsumi Matsumoto, Guy Munhoven, Alvaro Montenegro, and Kathy Tokos

The amount of time it [would take] until the CO_2 concentration in the air recovers substantially toward its original concentration [*in the absence of emissions*]

DEFINITIONS

Lifetime: Time required, in absence of anthropogenic emissions, until the CO_2 concentration in the air recovers substantially toward its original concentration.

Qualitative

Turnover time: Ratio of Stock to Flux out:

$$\tau_i^{\mathrm{to}} = \frac{S_i}{\sum_j F_{ij}} = \frac{S_i}{Q - \Delta S_i}$$

Delta Method

Requires a ***budget***. Need to specify which stock, which fluxes.

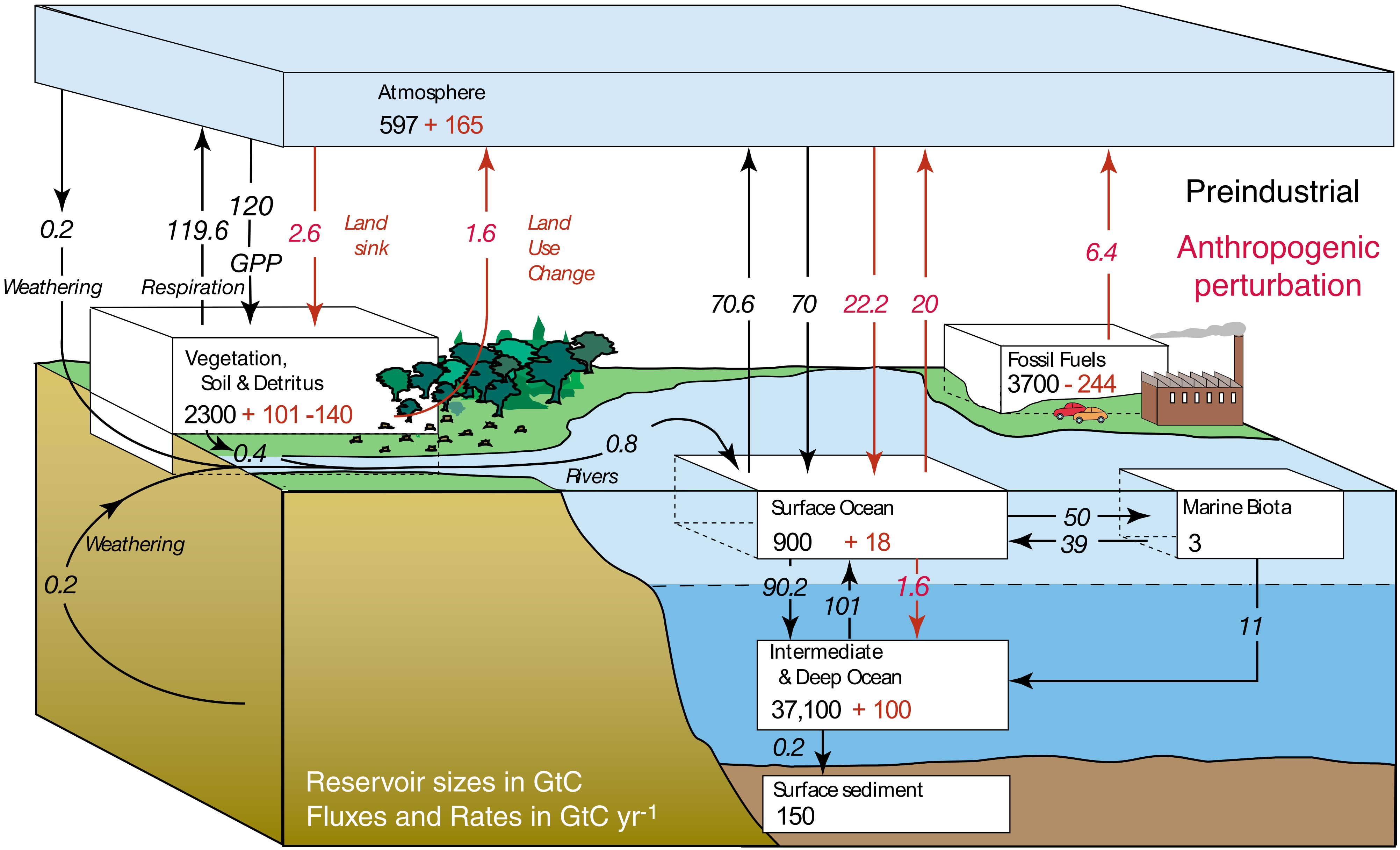
Adjustment time: Inverse of fractional removal rate in the absence of sources:

$$\tau_i^{\mathrm{adj}} = \frac{S_i}{\left(-\dfrac{dS_i}{dt}\right)}, \quad Q^{\mathrm{ant}} = 0$$

Requires a ***numerical model***

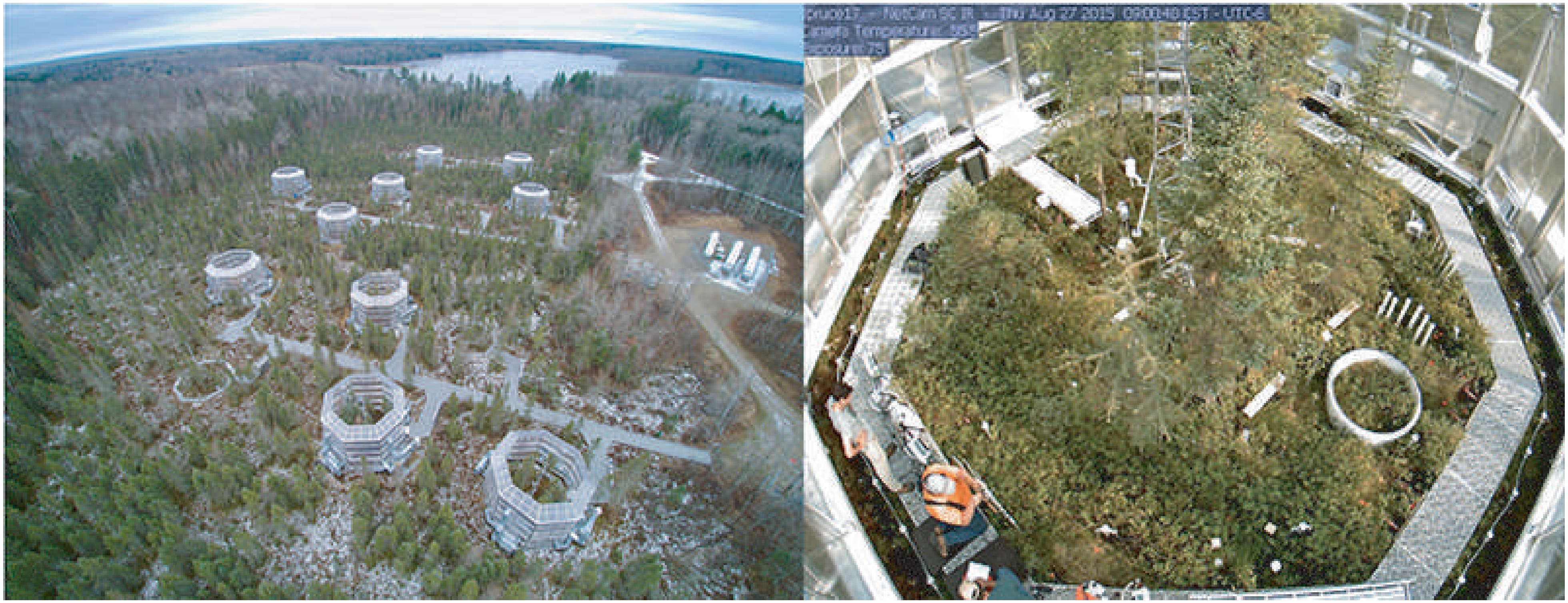
Observationally based Global CO_2 budget And Turnover time Of Anthropogenic CO_2

CO_2 STOCKS, *FLUXES*



AR4 (2007), Fig. 7.3
after Sarmiento & Gruber, Phys. Today (2002)

Department of Energy's Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment



Marcell Experimental Forest, Northern Minnesota

Examine vulnerability of wetland ecosystems to important climate change variables.

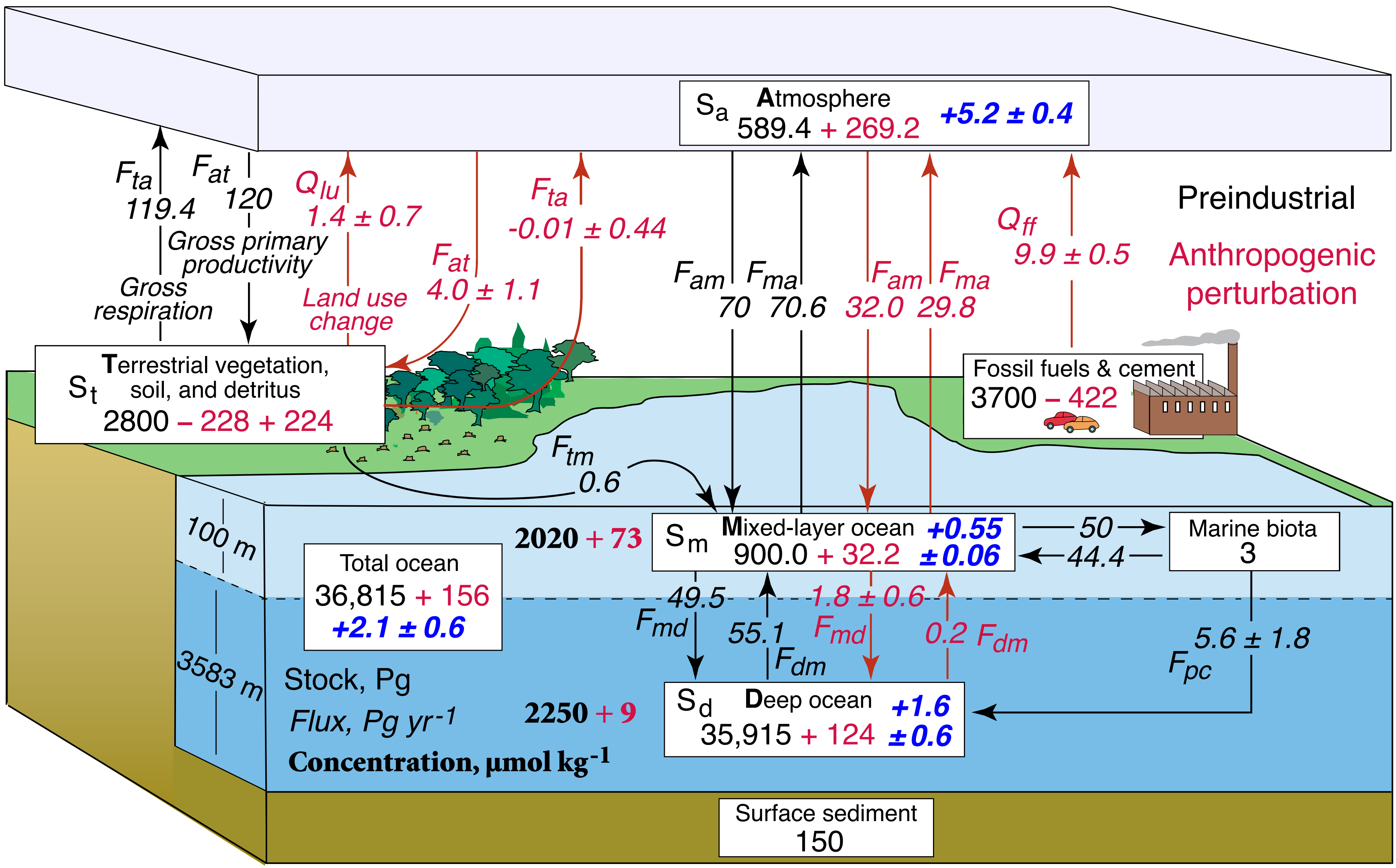
$50 million experiment, funded by the Department of Energy, projected to run for 10 years.

10 (40 ft diameter, 30 ft tall) open-topped, controlled-environment enclosures.

Atmosphere and soil (peat) in the enclosures maintained at (0, +4, +8, +12, and +16 ˚F) relative to ambient.

Carbon dioxide approximately doubled in half of the chambers.

CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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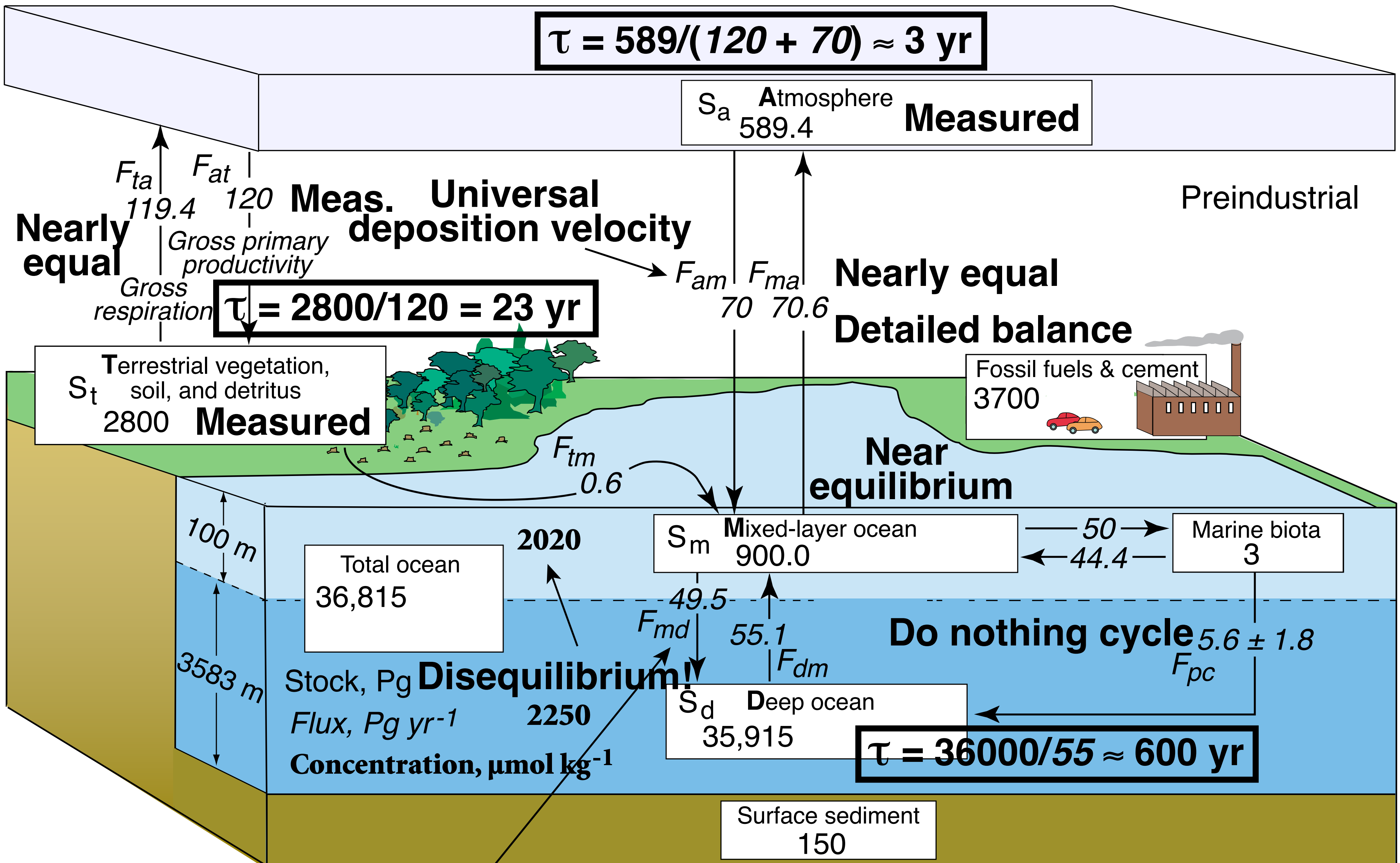
CO_2 STOCKS, *FLUXES*

Steady state



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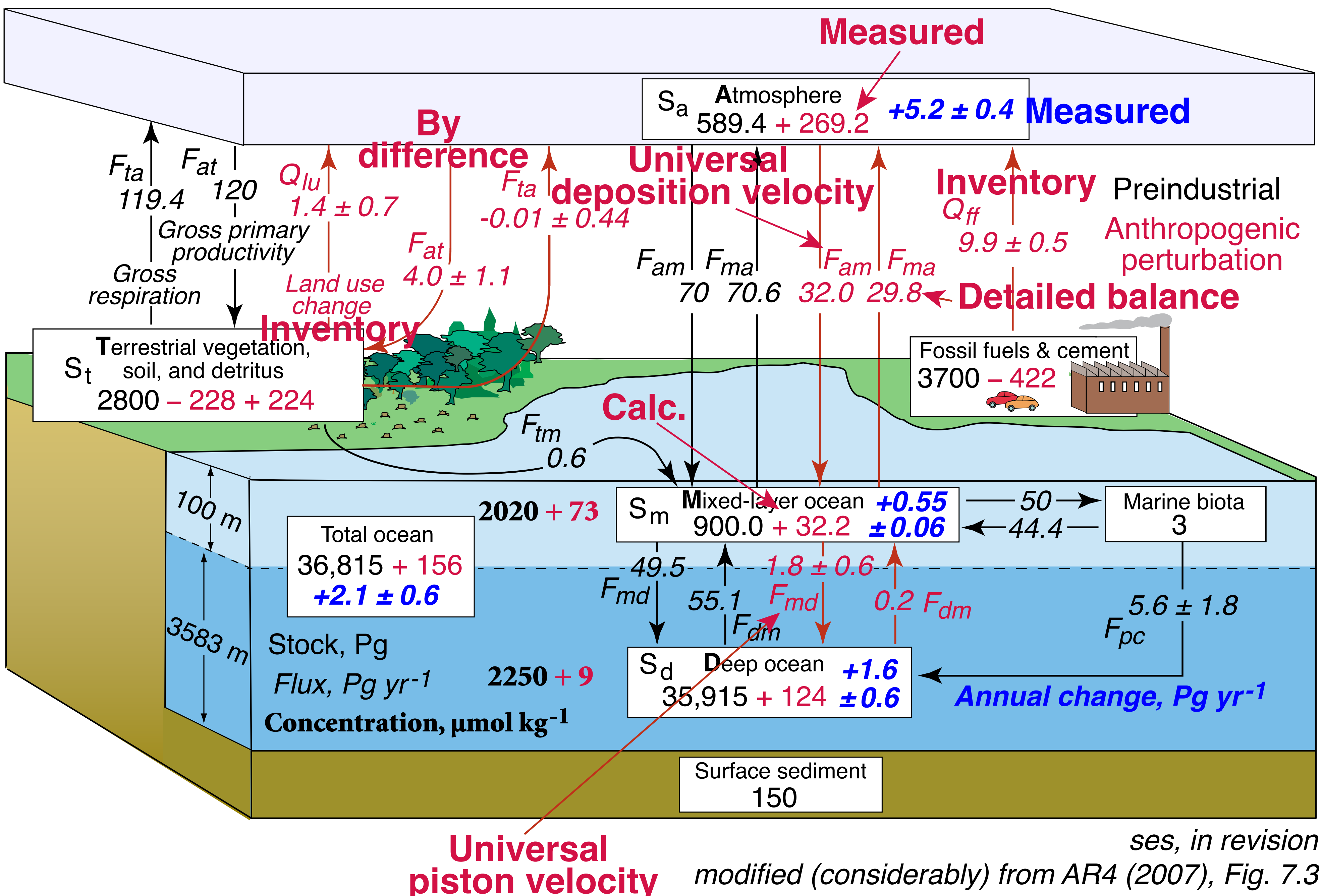
CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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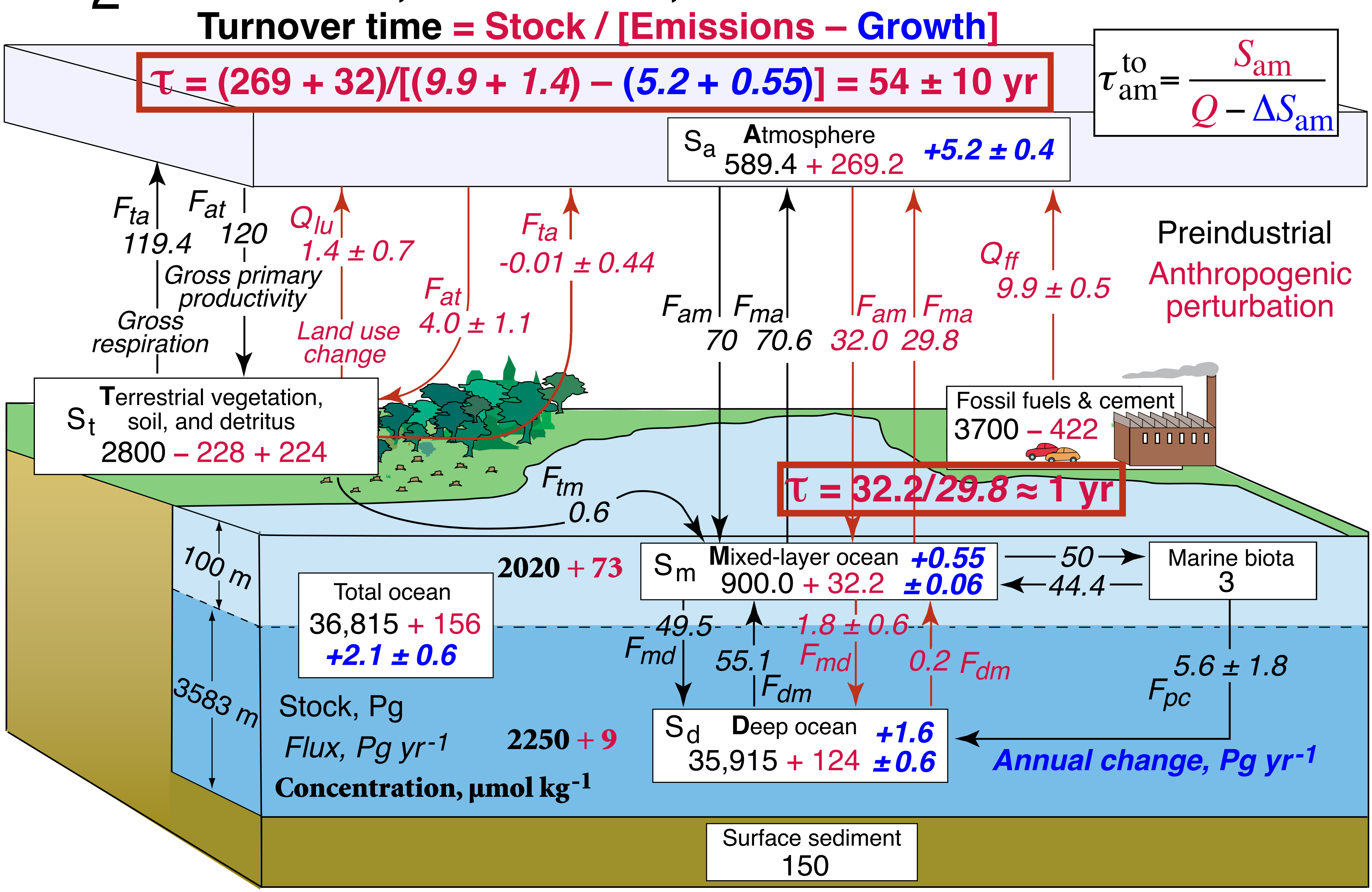
CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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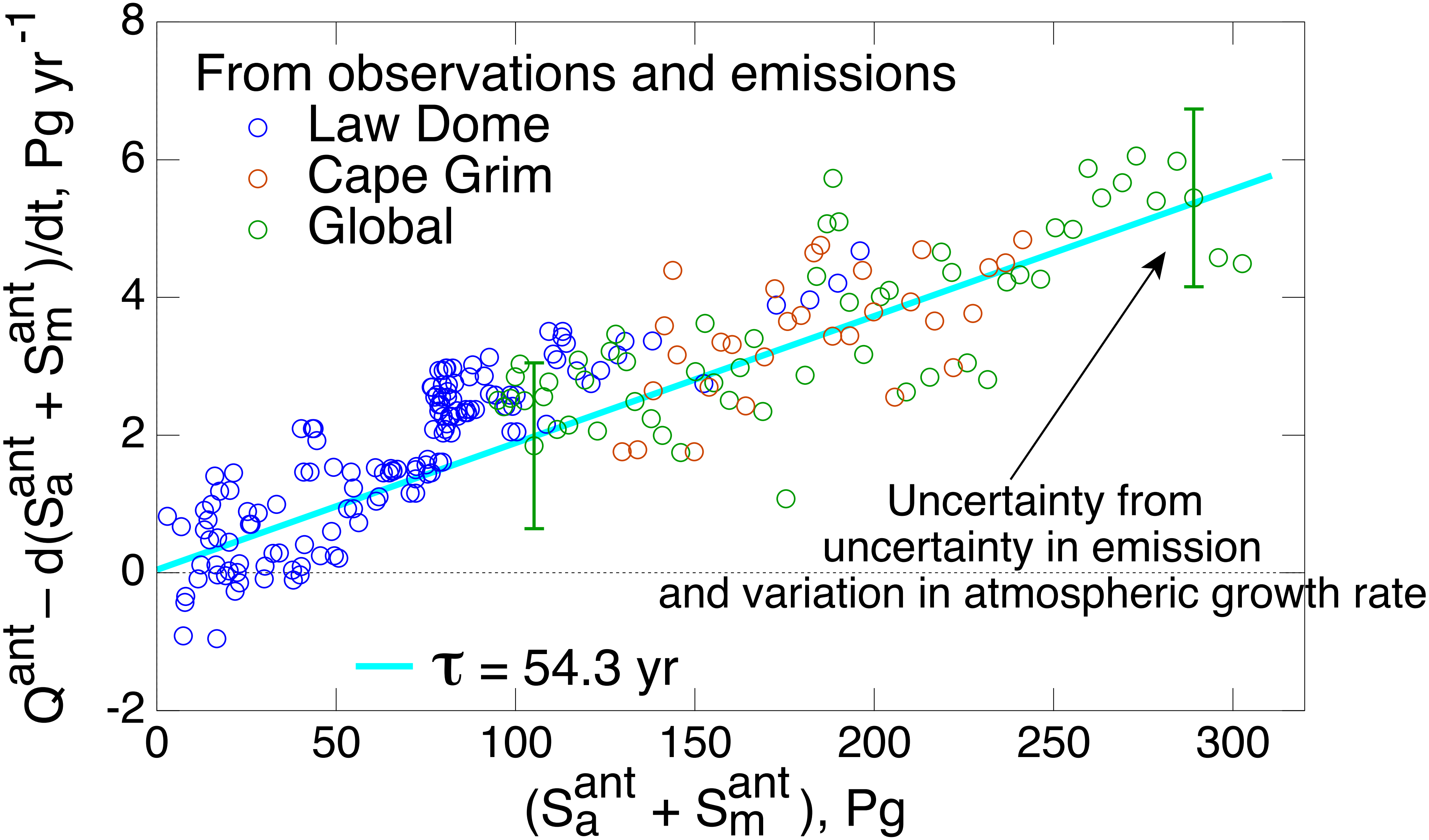
modified (considerably) from AR4 (2007), Fig. 7.3

after Sarmiento & Gruber, Phys. Today (2002)

SINK RATE INTO TERRESTRIAL BIOSPHERE PLUS DEEP OCEAN



Assumed sink to terrestrial biosphere plus deep ocean agrees with sink based on measured increase in atmospheric stock and inventoried emissions.

Model for Anthropogenic CO_2

THE DIFFERENTIAL EQUATIONS

$$\frac{dS_{\mathrm{a}}}{dt} = -k_{\mathrm{am}}\left(S_{\mathrm{a}} - S_{\mathrm{a}}^{\mathrm{eq}}\right) + k'_{\mathrm{ma}}\left(S_{\mathrm{m}} - S_{\mathrm{m}}^{\mathrm{eq}}\right) - k_{\mathrm{at}}S_{\mathrm{a}} + k_{\mathrm{ta}}S_{\mathrm{t}} - F_{\mathrm{tm}}^{\mathrm{pi}} + Q_{\mathrm{ff}}(t) + Q_{\mathrm{lu}}(t)$$

$$\frac{dS_{\mathrm{m}}}{dt} = k_{\mathrm{am}}\left(S_{\mathrm{a}} - S_{\mathrm{a}}^{\mathrm{eq}}\right) - k'_{\mathrm{ma}}\left(S_{\mathrm{m}} - S_{\mathrm{m}}^{\mathrm{eq}}\right) - k_{\mathrm{md}}S_{\mathrm{m}} + k_{\mathrm{dm}}S_{\mathrm{d}} + F_{\mathrm{tm}}^{\mathrm{pi}} - F_{\mathrm{pc}}$$

$$\frac{dS_{\mathrm{d}}}{dt} = k_{\mathrm{md}}S_{\mathrm{m}} - k_{\mathrm{dm}}S_{\mathrm{d}} + F_{\mathrm{pc}}$$

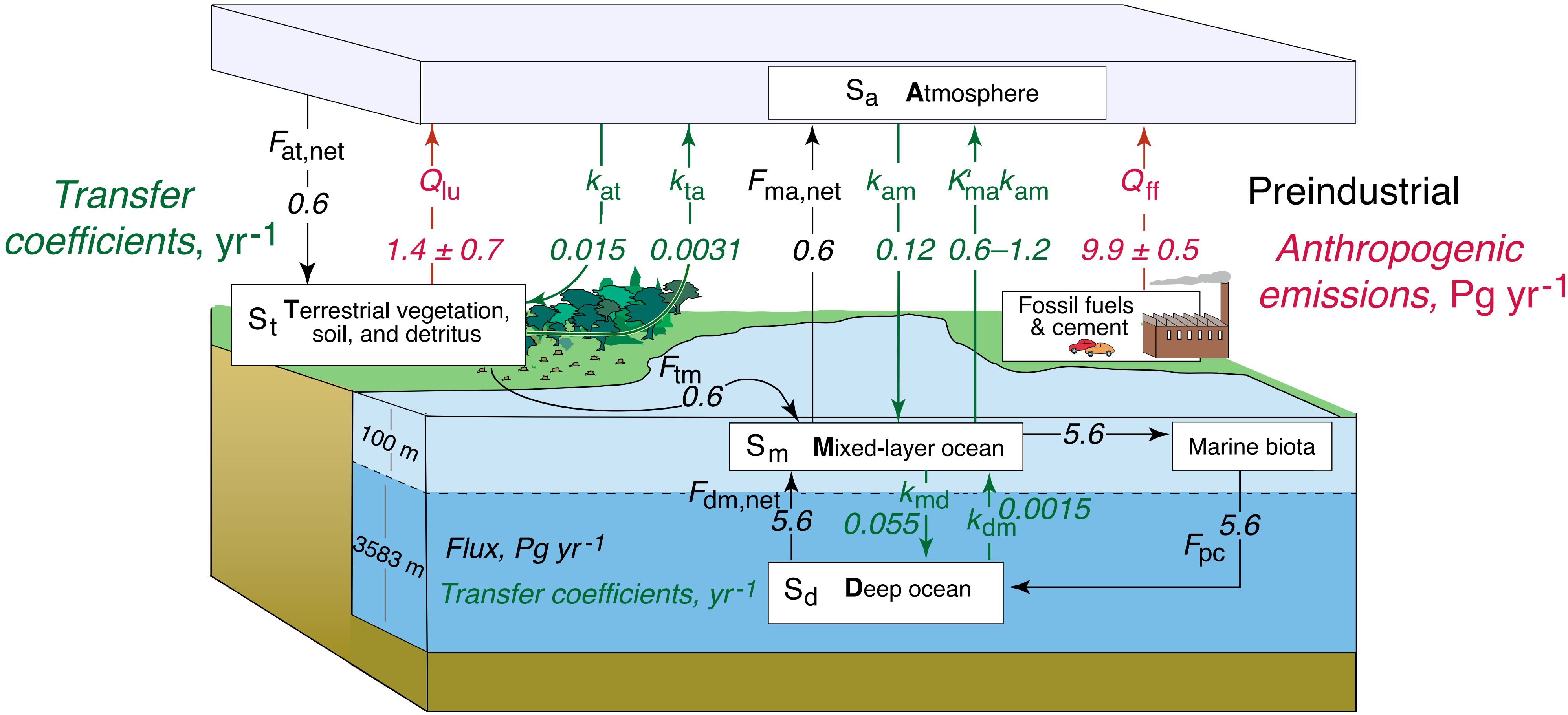
$$\frac{dS_{\mathrm{t}}}{dt} = k_{\mathrm{at}}S_{\mathrm{a}} - k_{\mathrm{ta}}S_{\mathrm{t}} - Q_{\mathrm{lu}}(t)$$

Four coupled ordinary differential equations.

Slightly nonlinear because k'_{ma} depends weakly on S_{m}.

Required: Transfer coefficients, emissions, initial conditions

TRANSFER COEFFICIENTS FOR ANTHRO CO_2



$\boxed{k_{am}} = F_{am}^{pi} / S_a^{pi}$; global mean deposition velocity **Geophysical property**

$k_{ma} = k_{am} K'_{am}$; $K'_{am} = (dS_a/dS_m)_{eq}$, a known function of S_a, 5–10 **Acid dissoc chem**

$k_{md} z_m = k_{dm} z_d = \boxed{v_p}$; global mean piston velocity, 5.5 m yr **Geophys ppty: from obs'd global heat uptake rate**

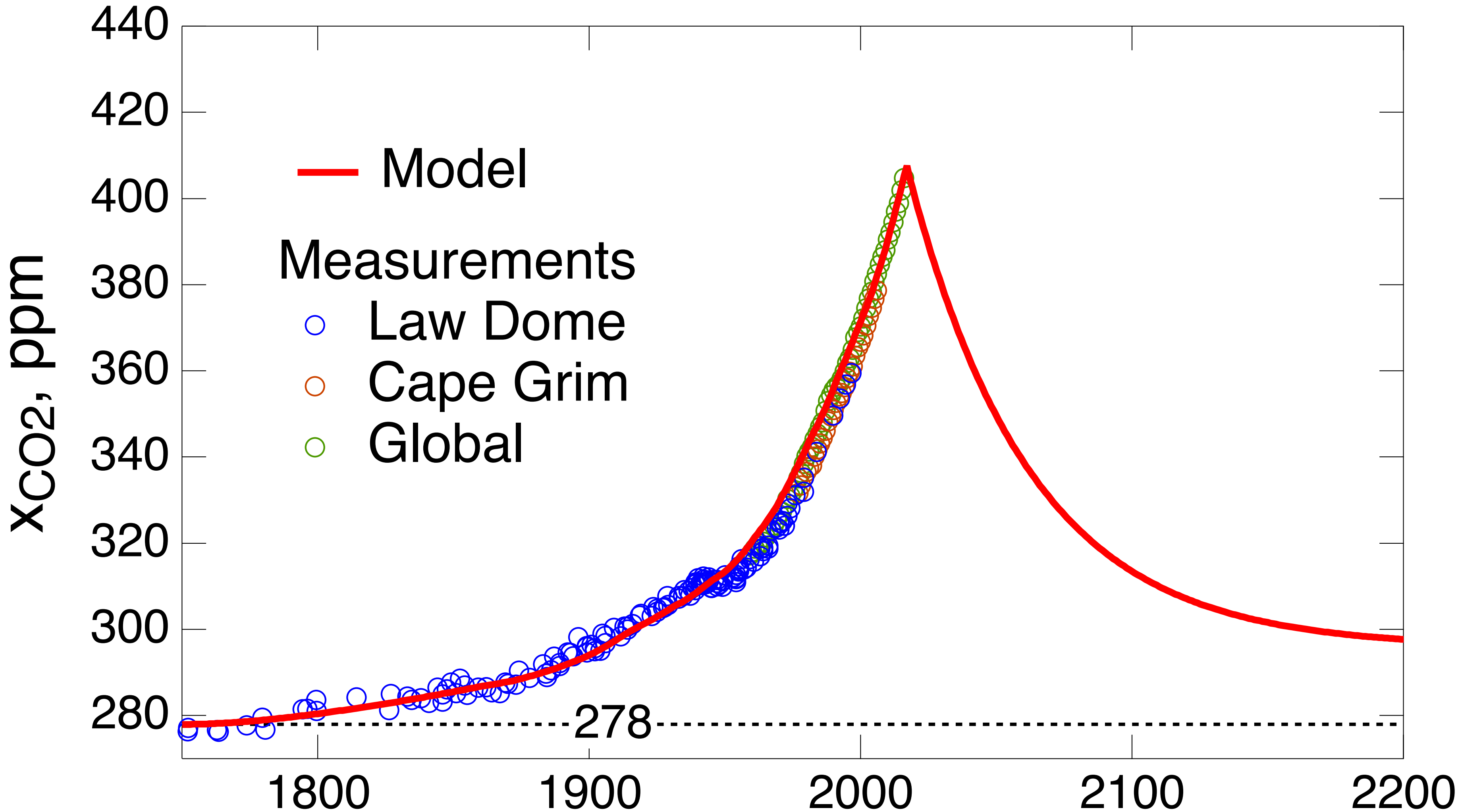
$\boxed{k_{at}} = [(Q_{tot} - dS_a/dt - dS_m/dt - dS_d/dt)/S_{a,ant}]_{2016}$ **By difference** **CO_2-specific Based on present budget**

$k_{ta} = k_{at} (S_a^{pi}/S_t^{pi}) - F_{tm}^{pi} / S_t^{pi}$ **Preindustrial steady state**

Three independent, observationally constrained parameters: $\boxed{k_{am},\ v_p, \text{ and } k_{at}}$

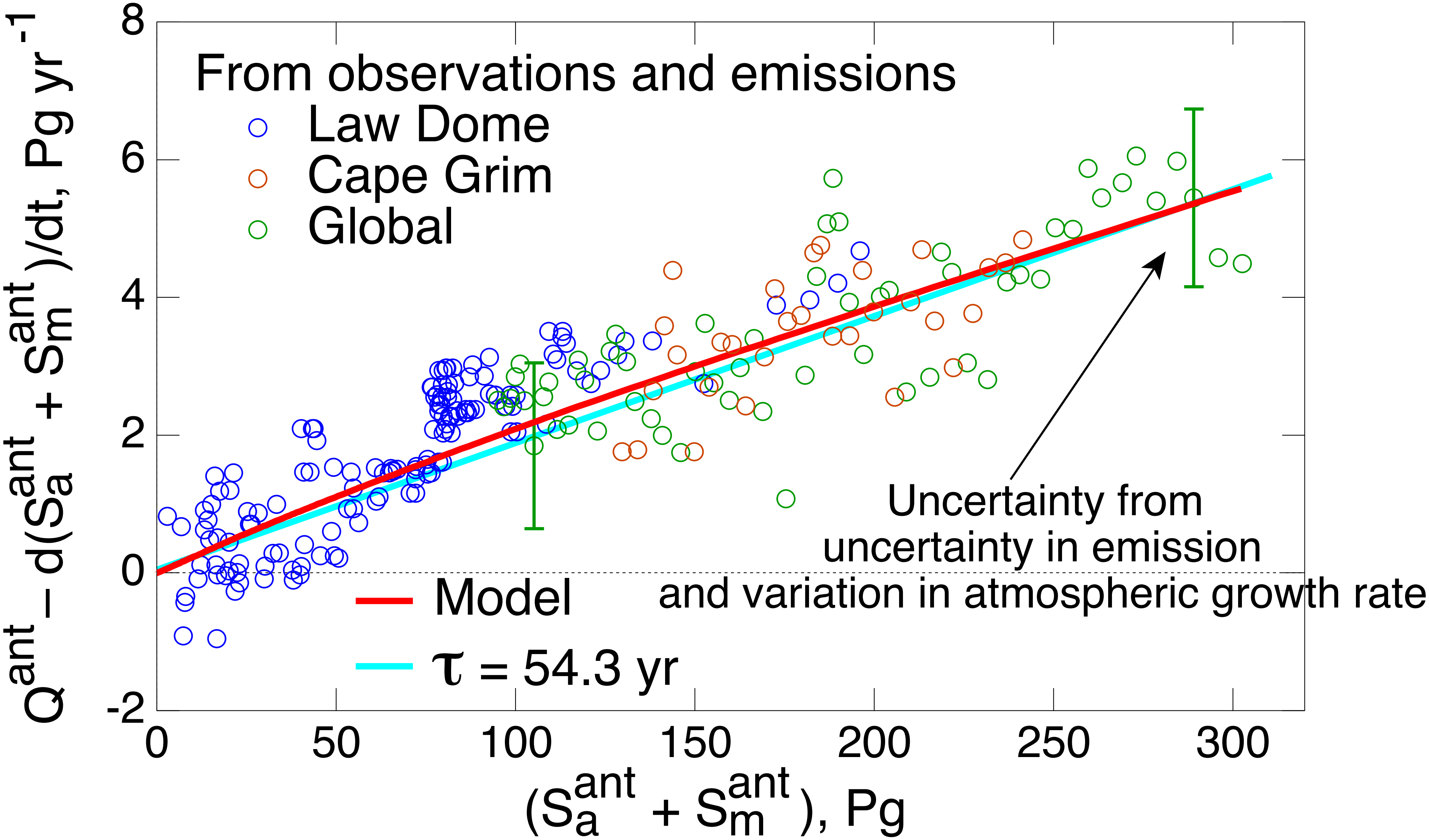
MODELED CO_2 MIXING RATIO

Abrupt cessation commencing in 2017



After abrupt cessation of emissions the CO_2 concentration in the atmosphere recovers substantially toward its original value on a time scale of several decades.

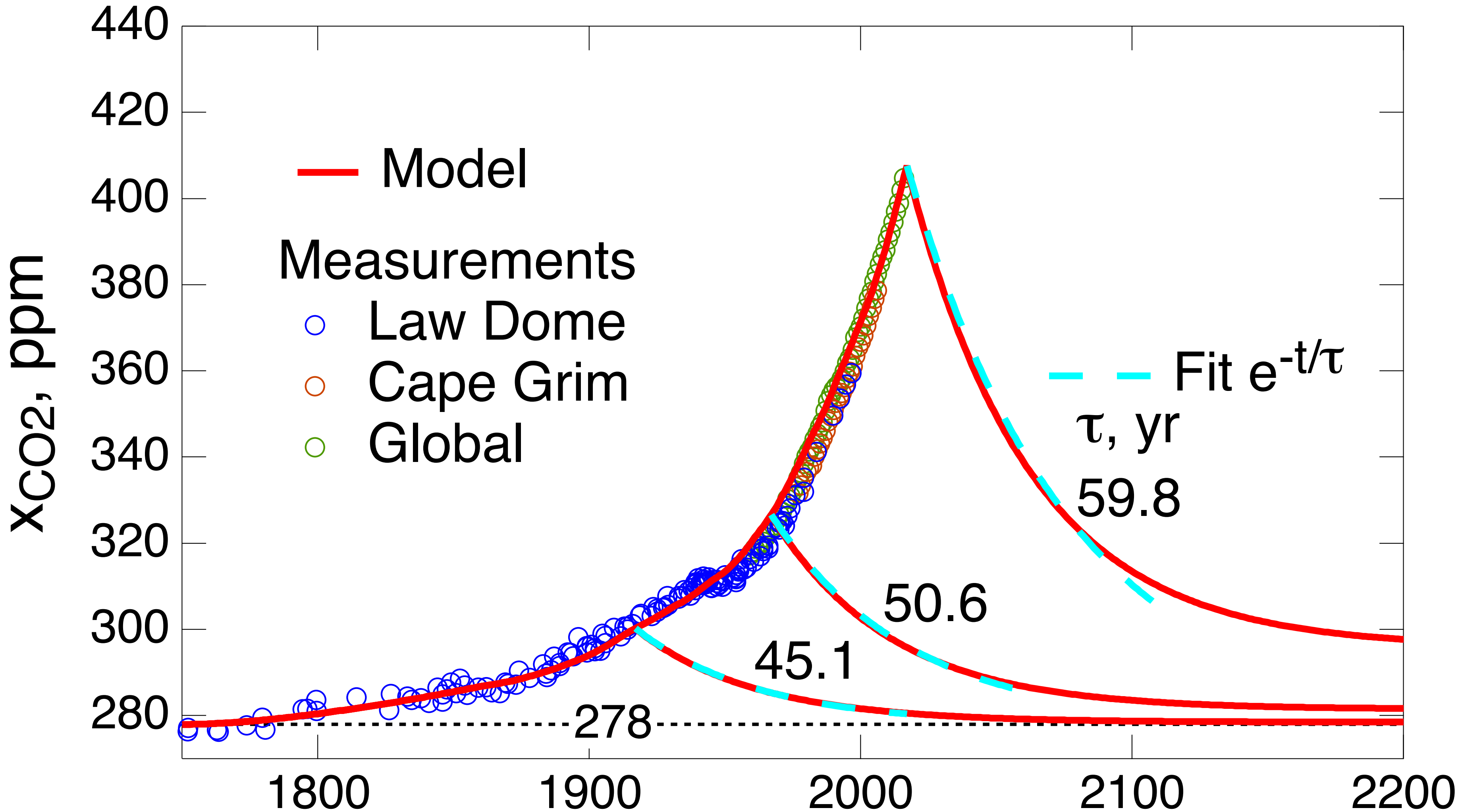
SINK RATE INTO TERRESTRIAL BIOSPHERE PLUS DEEP OCEAN



Assumed sink to terrestrial biosphere plus deep ocean agrees with sink based on measured ***and modeled*** increase in atmospheric stock and inventoried emissions.

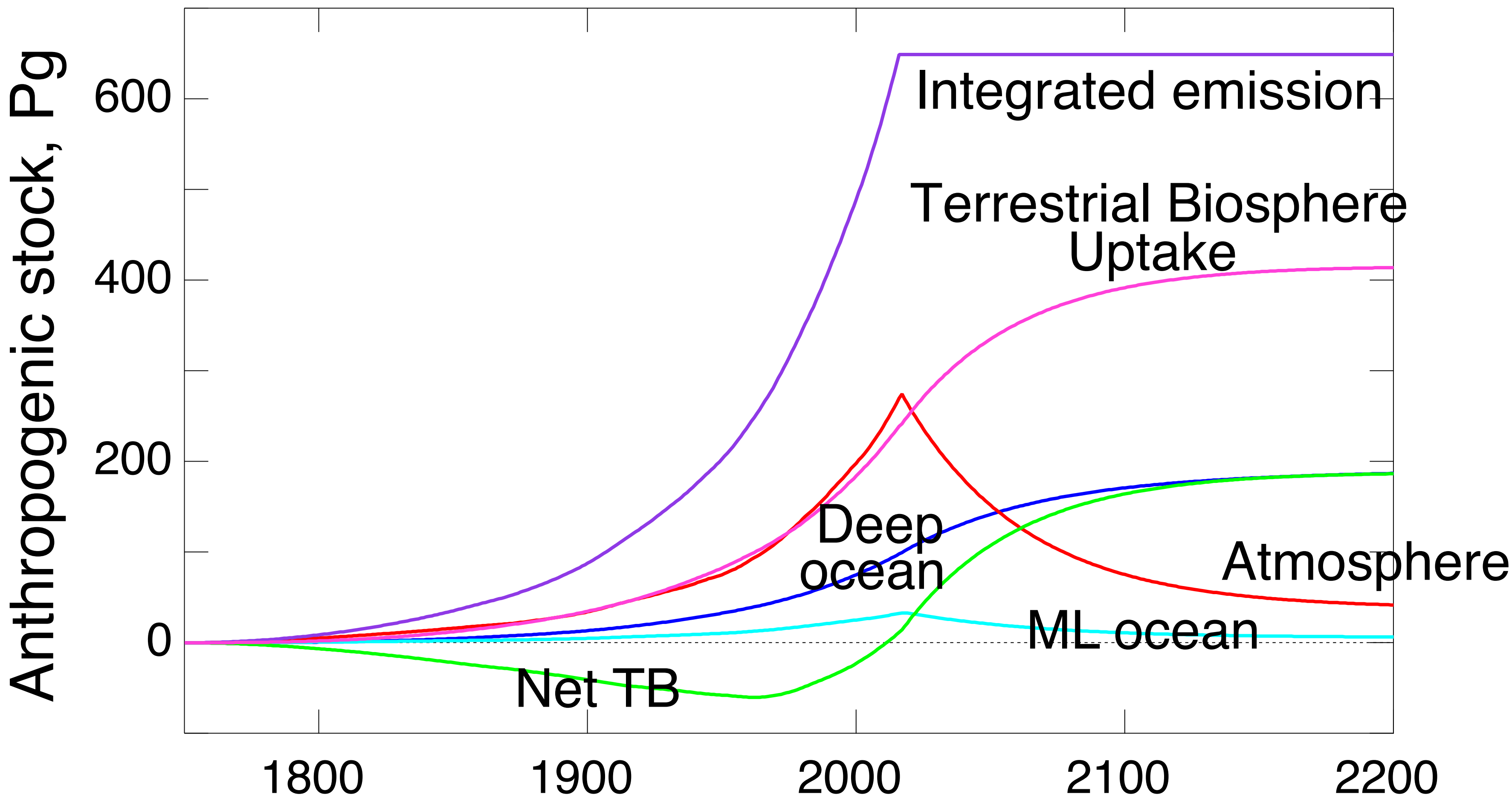
MODELED CO_2 MIXING RATIO

Abrupt cessation at three start times



Atmospheric CO_2 decreases nearly exponentially after cessation.
Time constant is roughly the same as turnover time (54 years).
Time constant increases with increasing date of cessation.

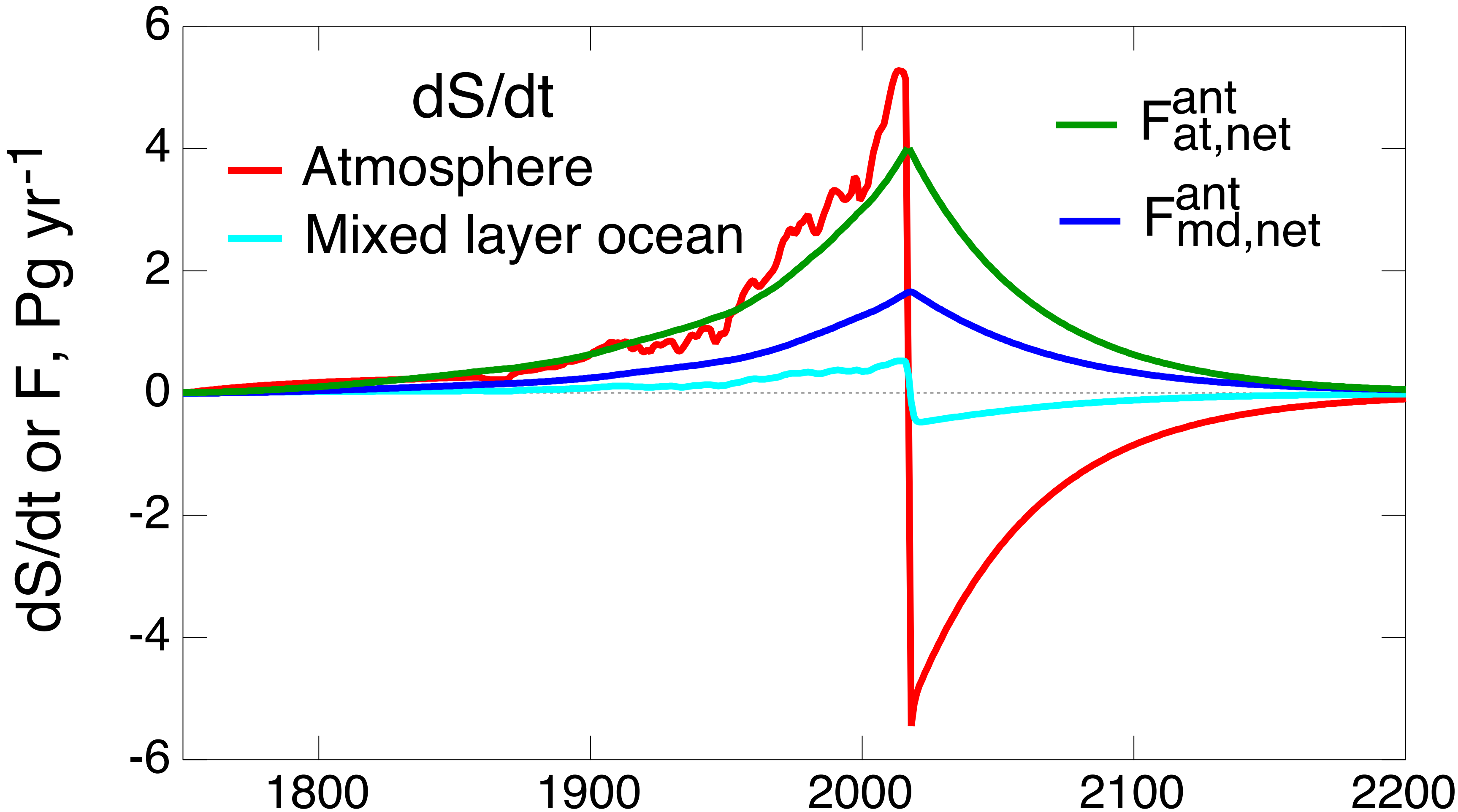
ANTHROPOGENIC STOCKS



Model allows examination of stocks in the several compartments.

Net TB is TB uptake minus net deforestation. Near zero at present.

FLUXES AND RATES OF CHANGE OF STOCKS



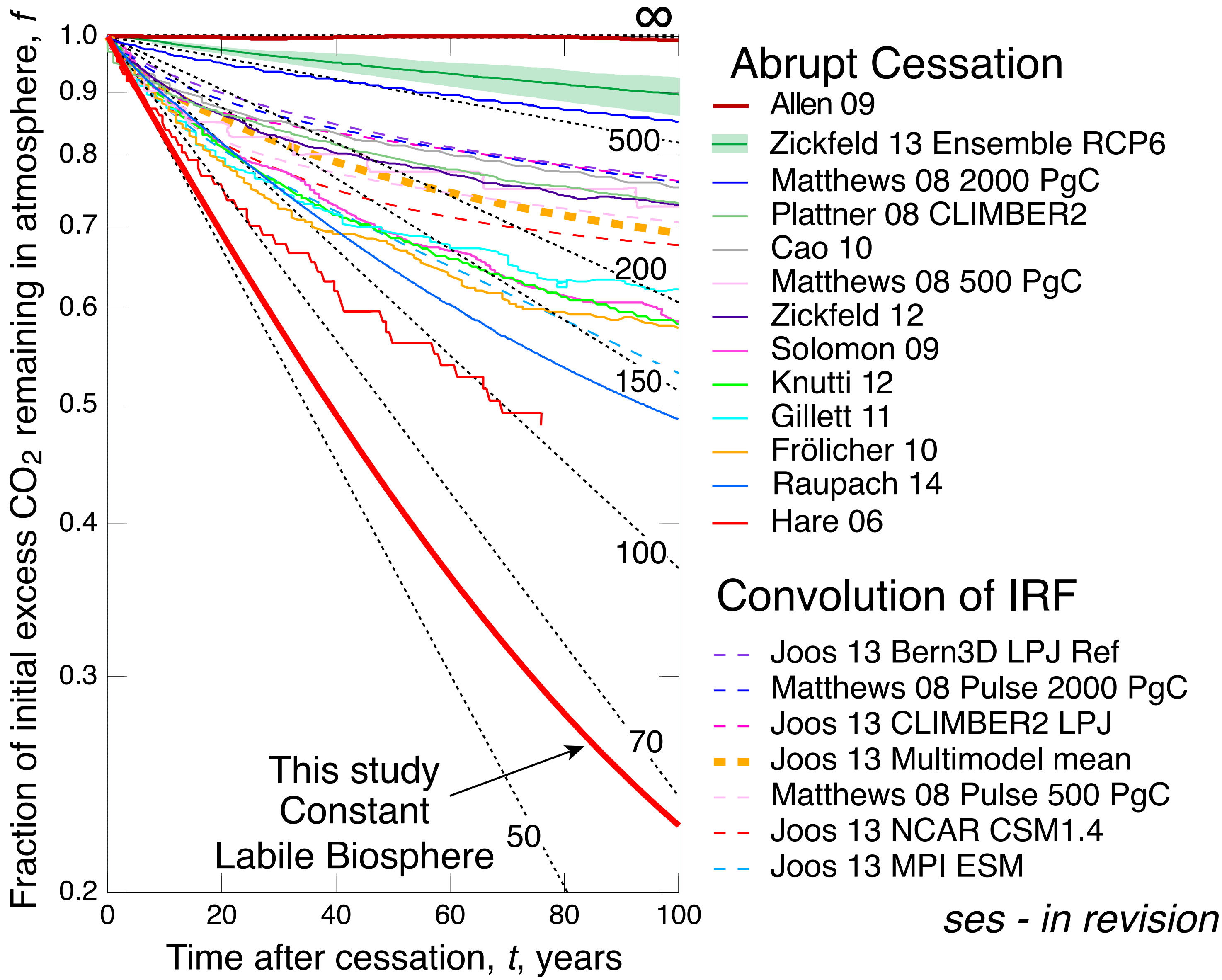
Stocks in Atmosphere and ocean Mixed Layer begin to decrease immediately on cessation (negative *dS/dt*).

Deep Ocean and Terrestrial Biosphere ***initially draw down CO_2 at prior rate***.

Sink rate initially unchanged. Stocks initially unchanged.
Turnover time of Atmos + ML initially unchanged.

DECAY OF EXCESS ATMOSPHERIC CO_2 AFTER ABRUPT CESSATION OF EMISSIONS

Calculated and redrawn from recent publications

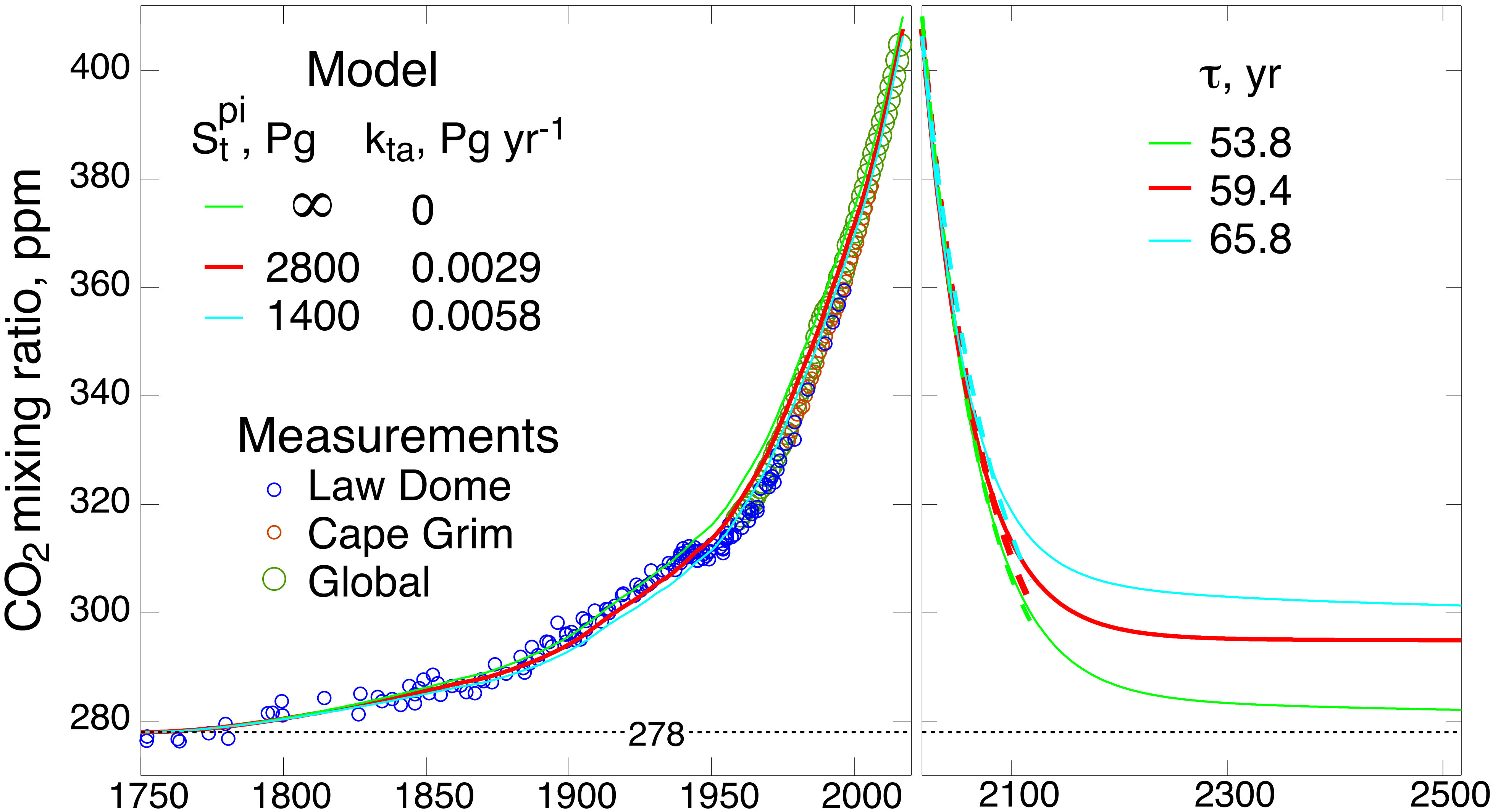


ses - in revision

Lifetime (60 yr) is ***much shorter than in prior studies.***

Senstivity to Stock in the Obdurate Biosphere

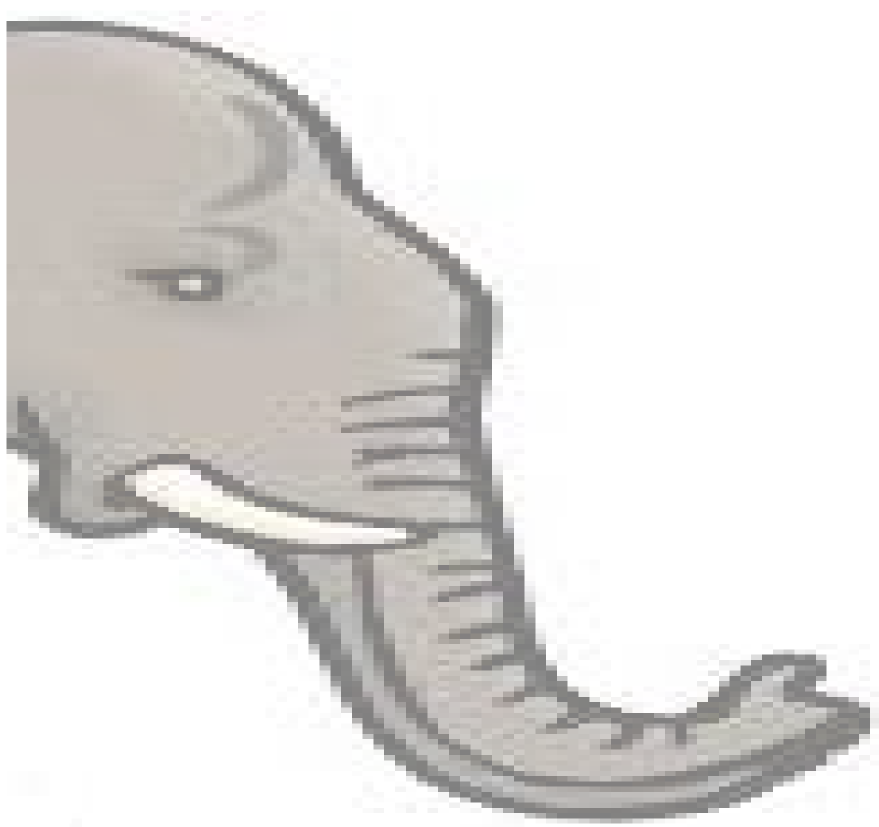
SENSITIVITY TO TERRESTRIAL BIOSPHERE STOCK



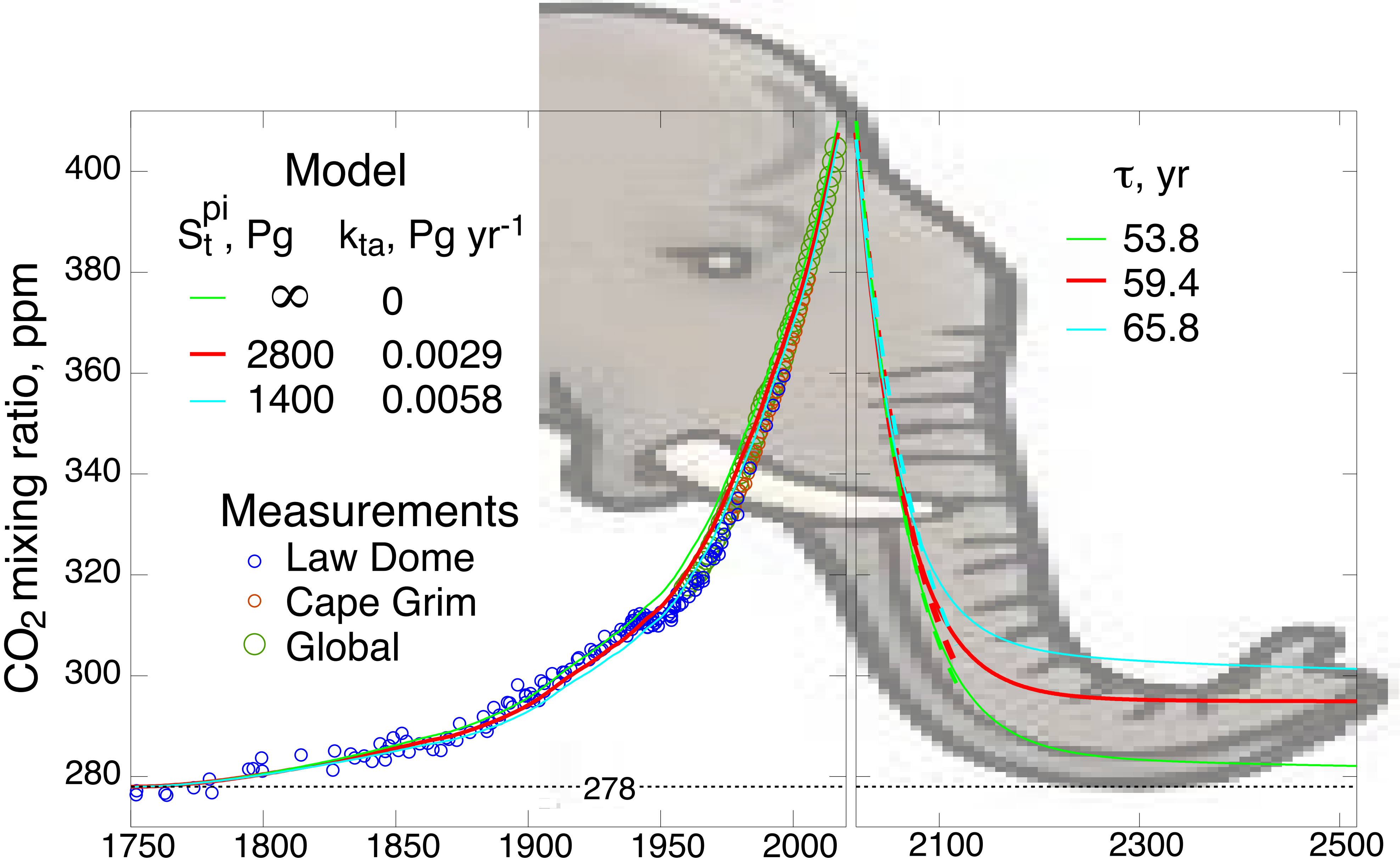
Rate and extent of decrease in atmospheric CO_2 are insensitive to ±100% change in transfer coefficient k_{ta}.

Von Neumann on Parameters

With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.



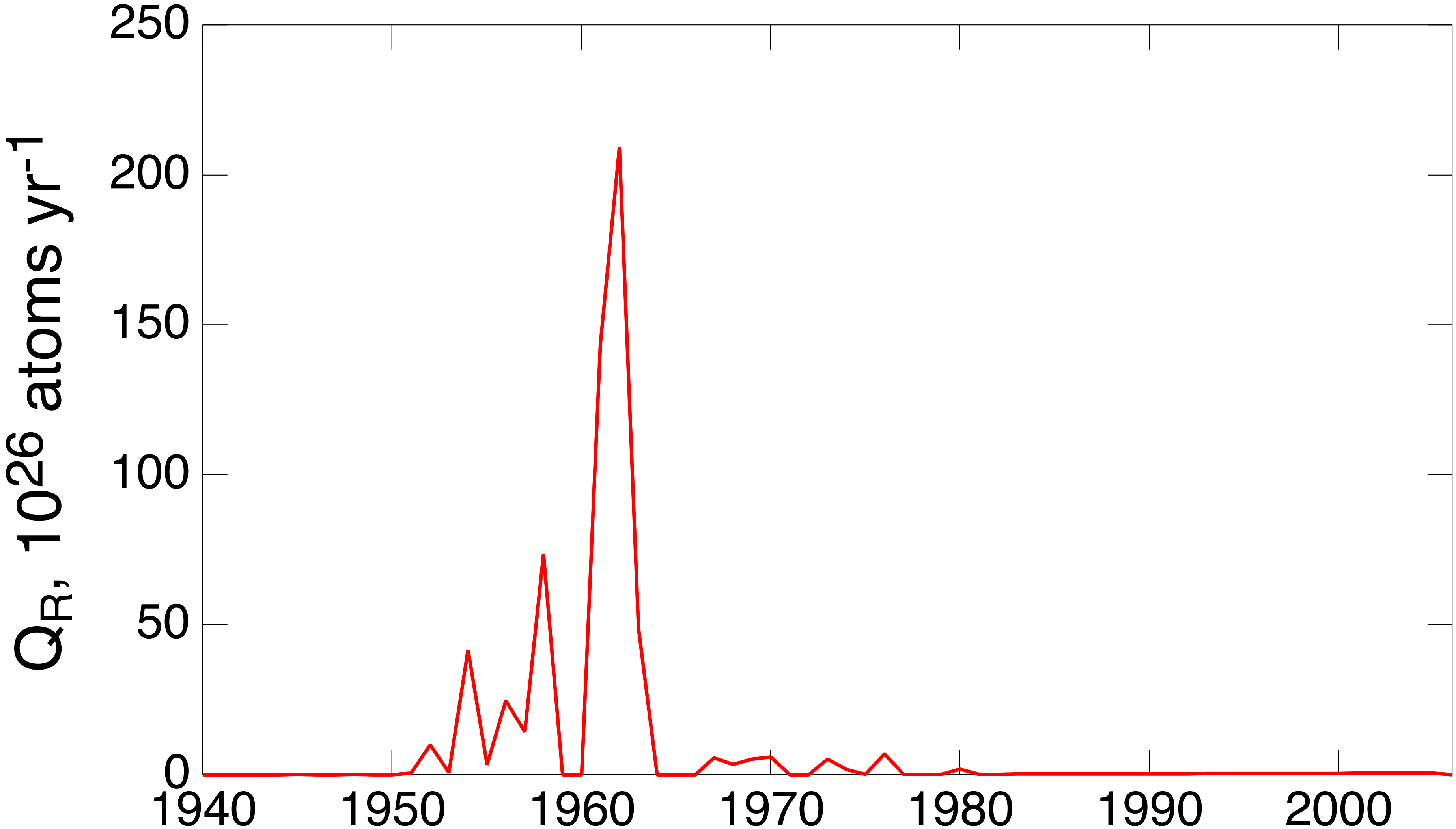
SENSITIVITY TO TERRESTRIAL BIOSPHERE STOCK



Rate and extent of decrease in atmospheric CO_2 are insensitive to ±100% change in transfer coefficient k_{ta}.

The Radiocarbon Problem

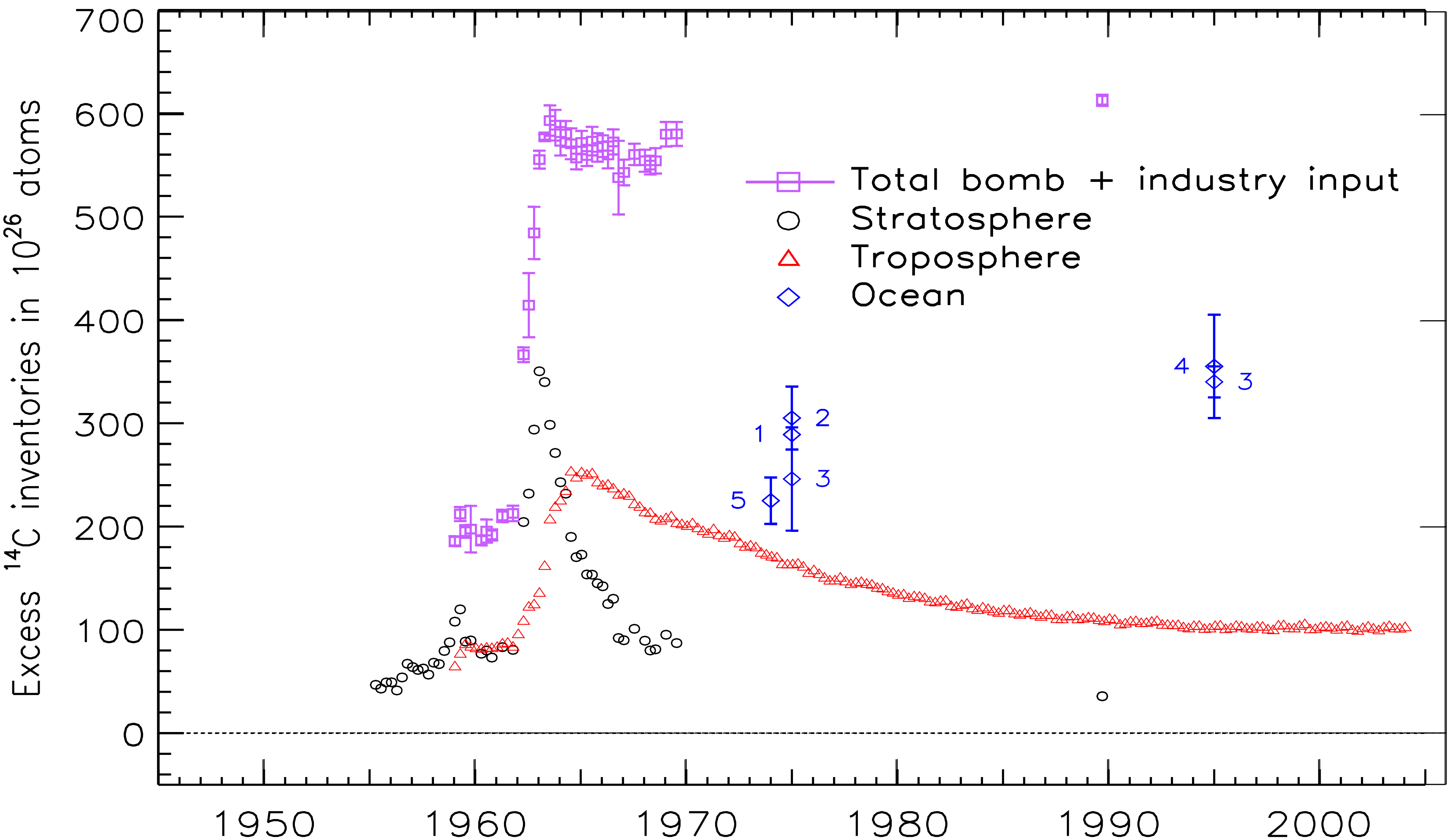
RADIOCARBON EMISSIONS



Produced by atmospheric testing of nuclear weapons.
Production abruptly ceased because of test ban treaty.
Minor production from nuclear industry.

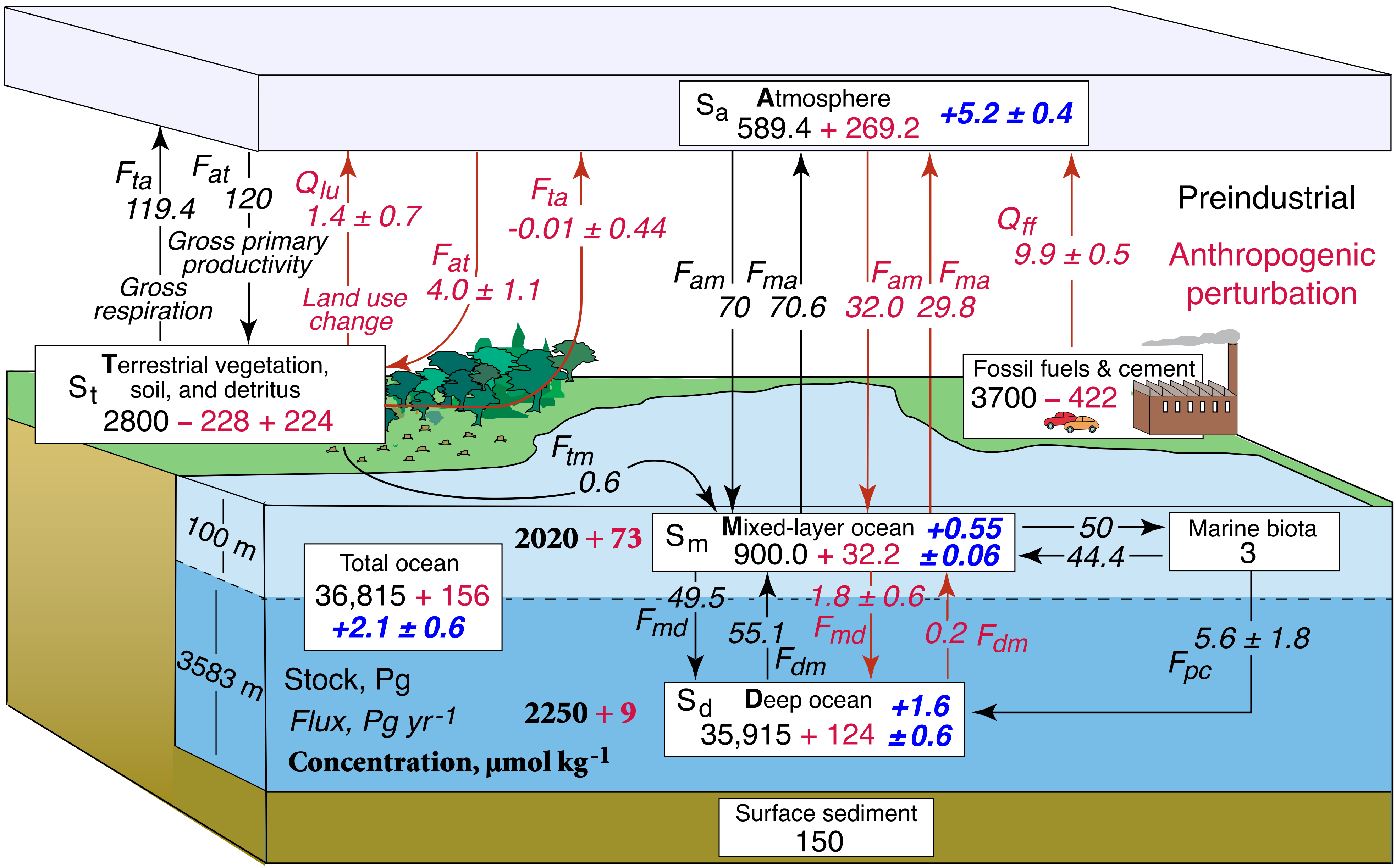
RADIOCARBON FROM ATMOSPHERIC WEAPONS TESTING

Observations



Observations: (1) Broecker et al. [85], (2) Broecker et al. [95], (3) Peacock [04], (4) Key et al. [04], (5) Hesshaimer et al. [94]; after Naegler and Levin, [06].

CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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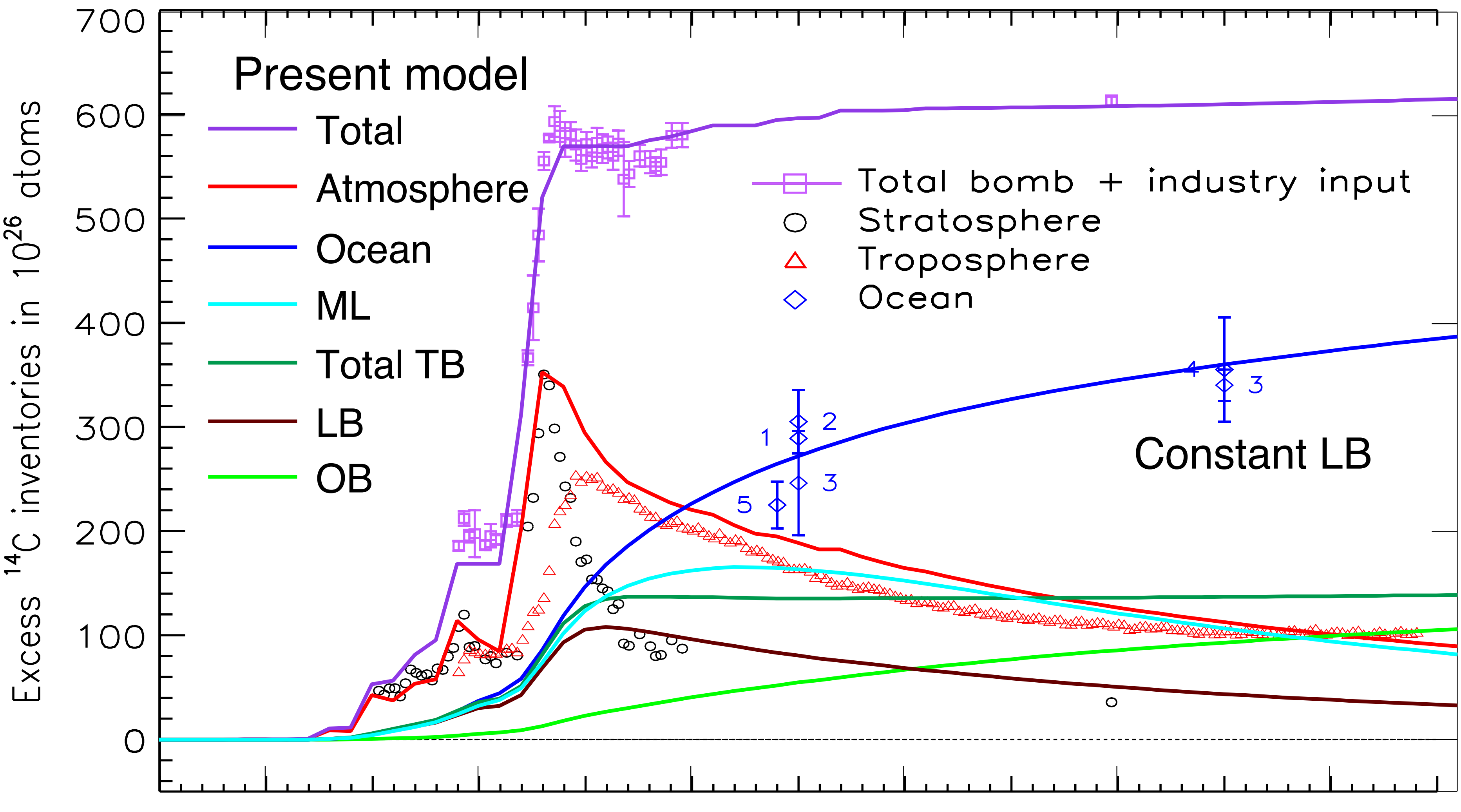
RADIOCARBON FROM ATMOSPHERIC WEAPONS TESTING

Observations and model



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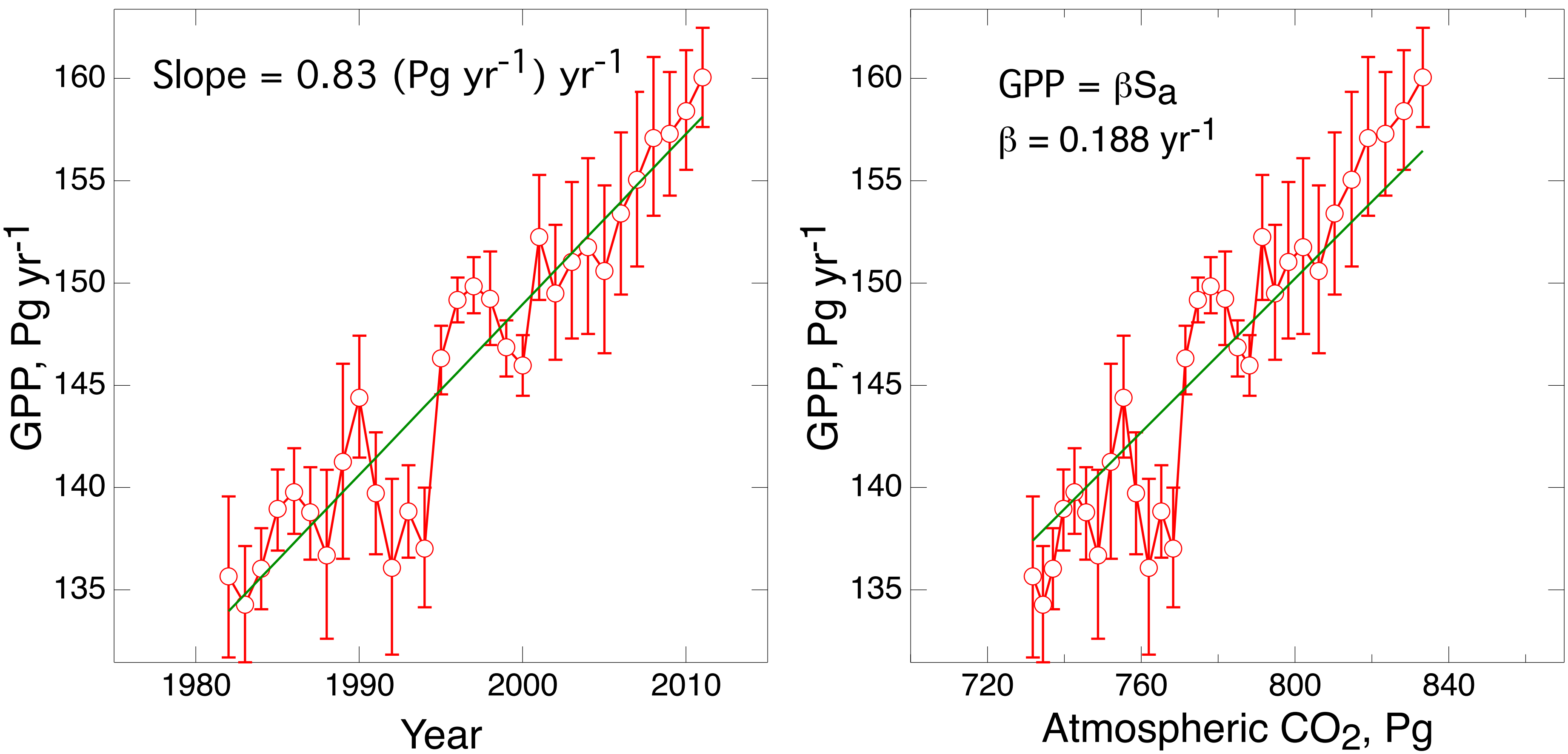
Senstivity to Increasing stock in the Labile Biosphere

PROPORTIONALITY OF GPP AND ATMOSPHERIC CO_2

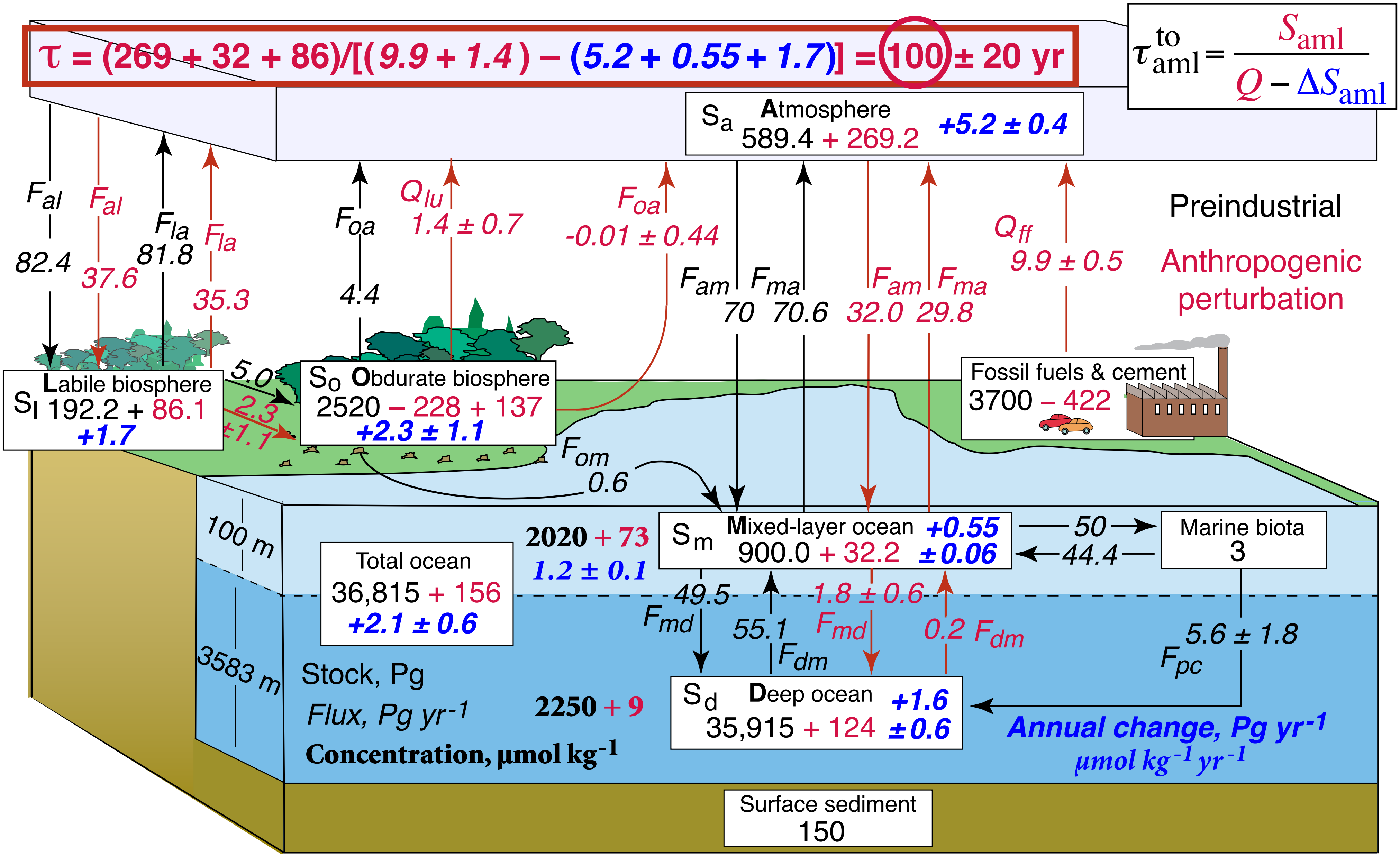
Based on observationally derived water use and water use efficiency



Cheng, Canadell, et al., Nature Comm., 2017

Fit (forced through origin) indicates proportionality of GPP to atmospheric CO_2.

CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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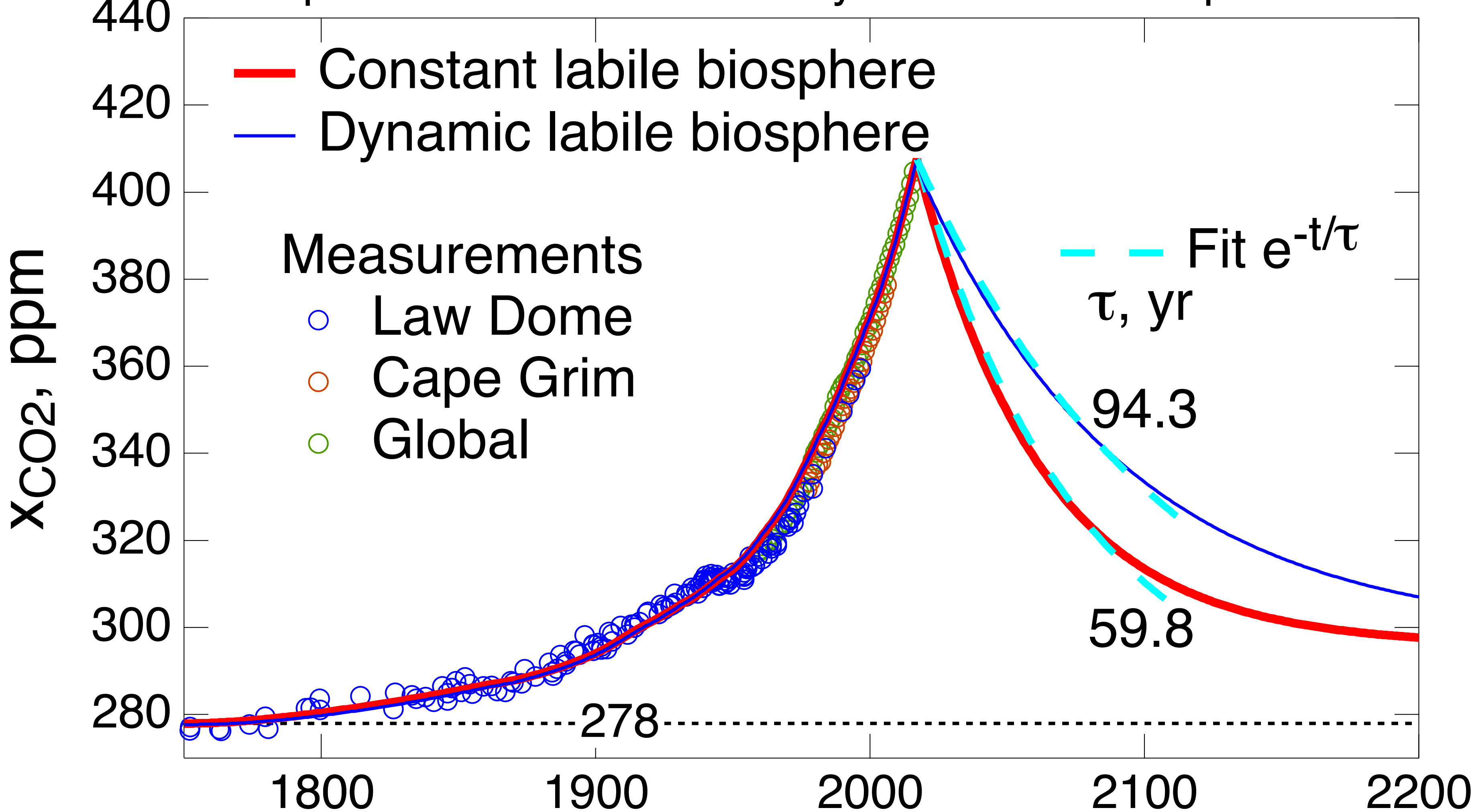
MODELED CO_2 MIXING RATIO

Abrupt cessation commencing in 2017

Comparison of constant and dynamic labile biosphere

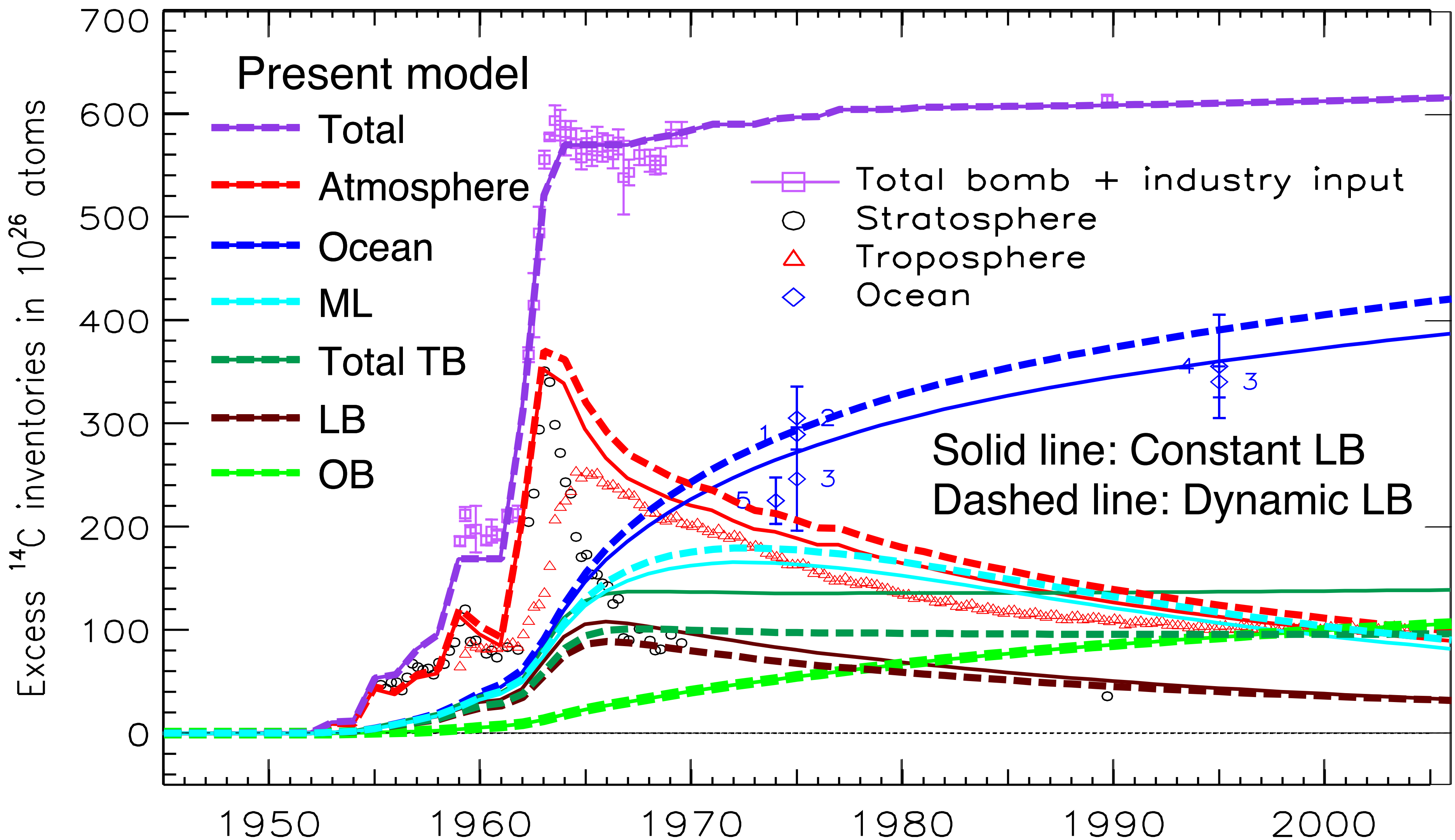


Both models agree equally well with observations.

The two models would seem to bracket the actual adjustment time.

RADIOCARBON FROM ATMOSPHERIC WEAPONS TESTING

Observations and model



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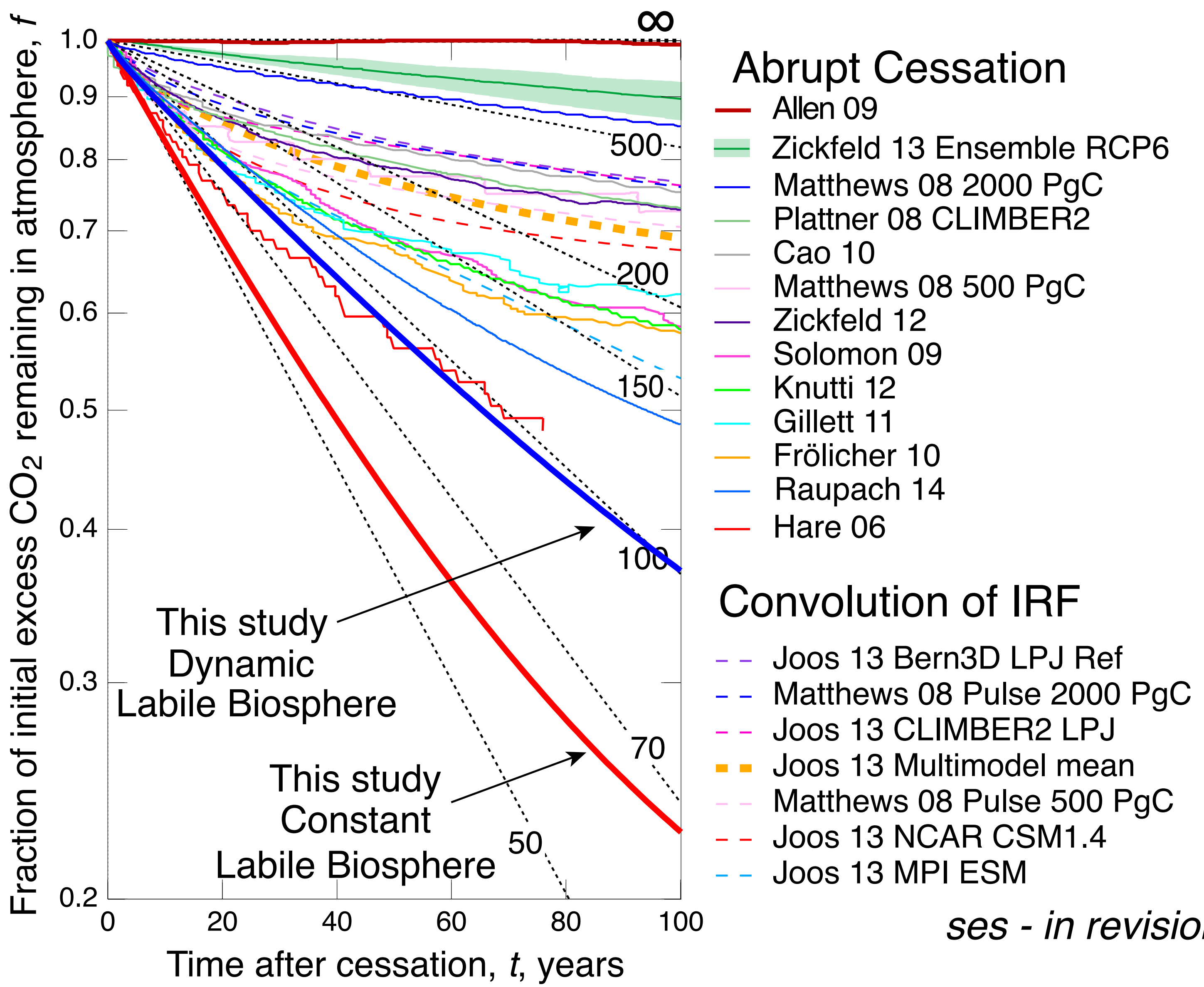

ses - in revision

Lifetime (60 – 100 yr) is ***much shorter than in prior studies.***

CONCLUSIONS AND IMPLICATIONS

The lifetime of excess atmospheric CO_2 is bracketed by multiple measures to about ***60 – 100 years***.

This lifetime is ***much shorter*** than virtually all previous estimates.

All this would be ***good news*** for strategies to meet climate change targets.

The simple model with 3 or 4 ***observationally constrained parameters*** accurately represents CO_2 over the Anthropocene and can be used with confidence to assess the consequences of prospective changes in emissions.