HOW LONG DOES ANTHROPOGENIC CO_2 STAY IN THE ATMOSPHERE?

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GISS Lunch Seminar

National Aeronautics and Space Administration
Goddard Institute for Space Studies

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OUR COLLECTIVE ENERGY USE

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

Equivalent to 100 watts

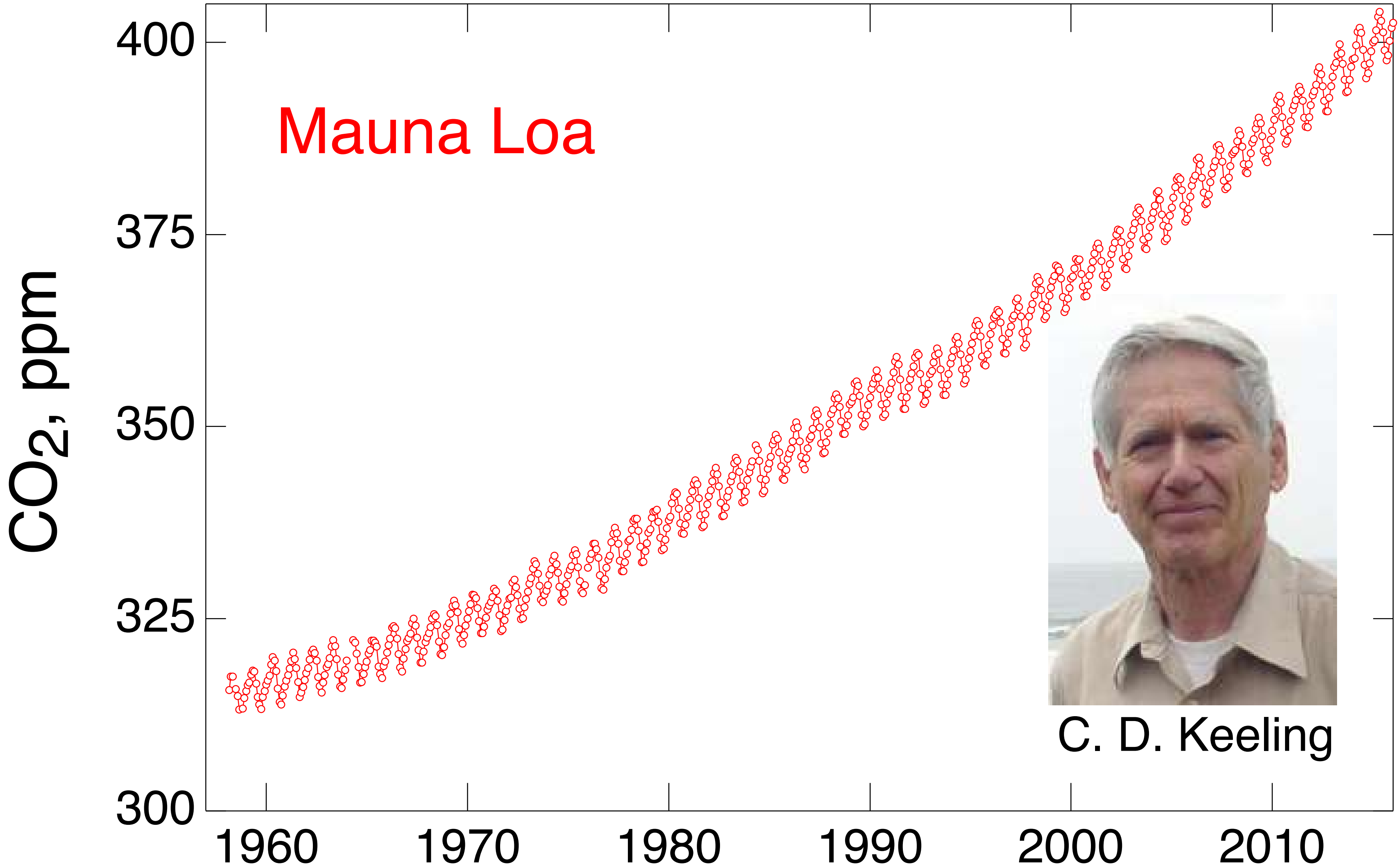
Per capita energy US use: 10,000 watts

100 100-watt light bulbs, 24 – 7

Equivalent to 100 people!

And all these “people” are exhaling CO_2!

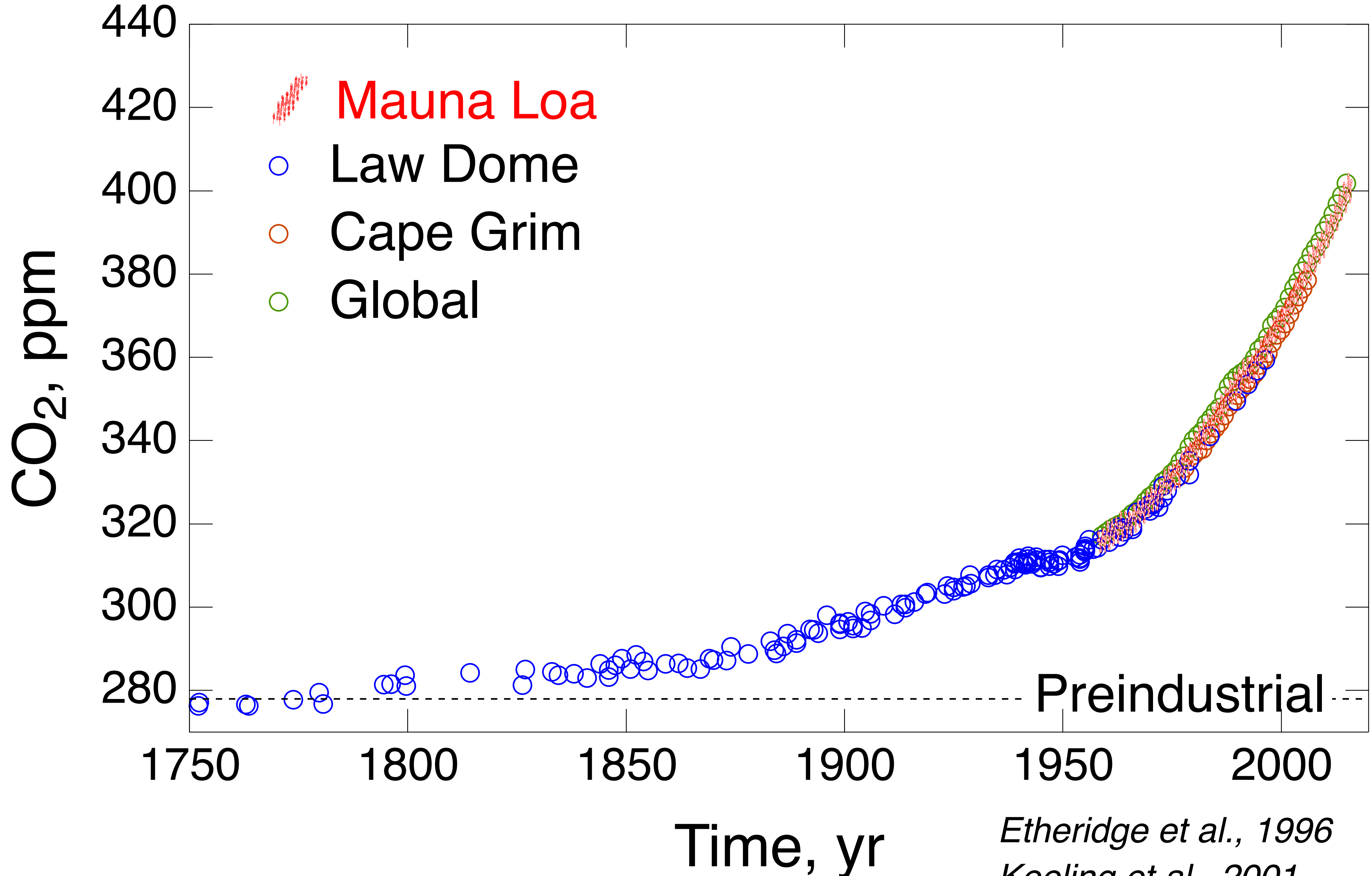
THE KEELING CURVE



Atmospheric CO_2 has increased substantially over this period.

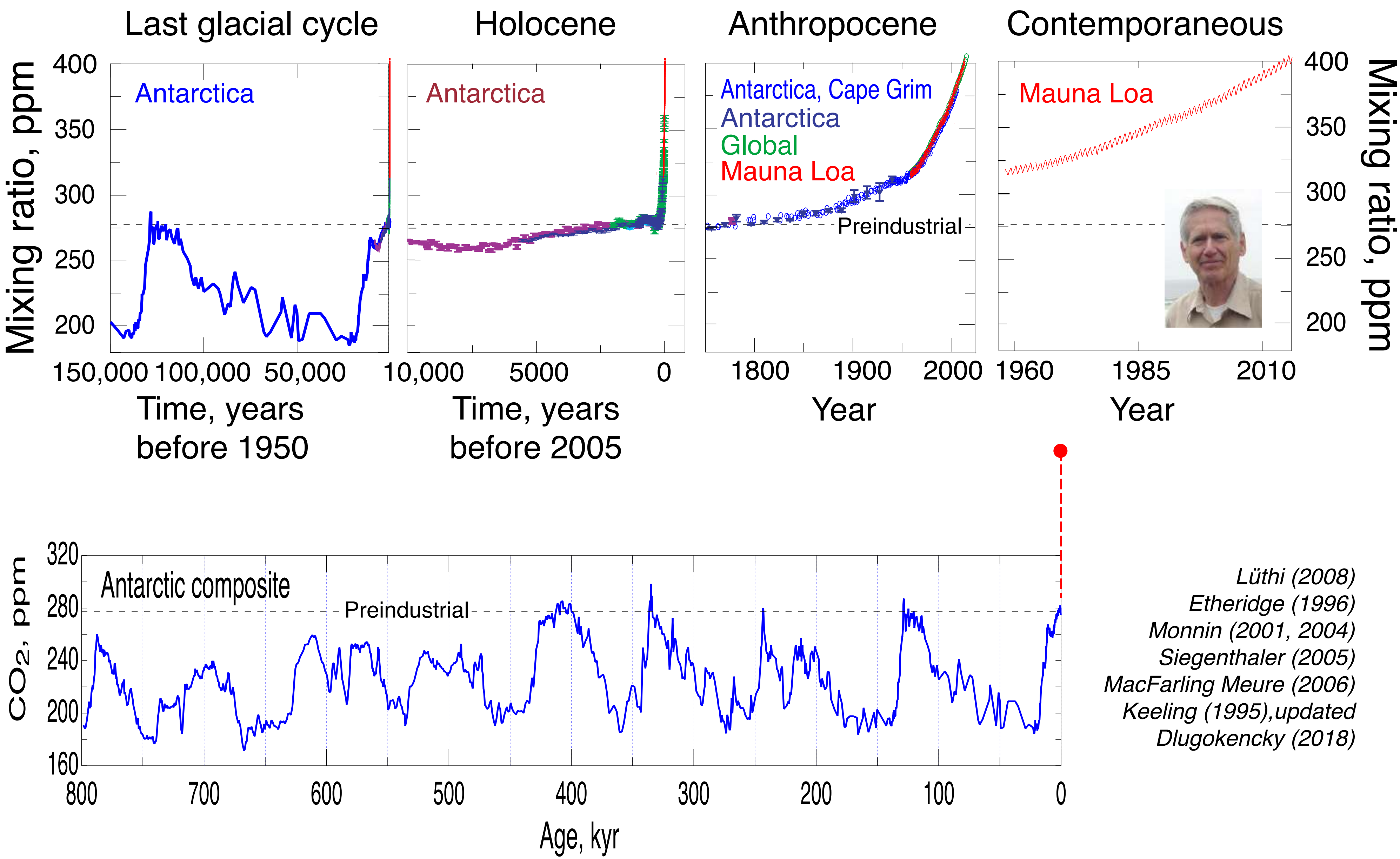
Annual cycle of monthly means is due to drawdown and release from the terrestrial biosphere.

CARBON DIOXIDE OVER THE ANTHROPOCENE



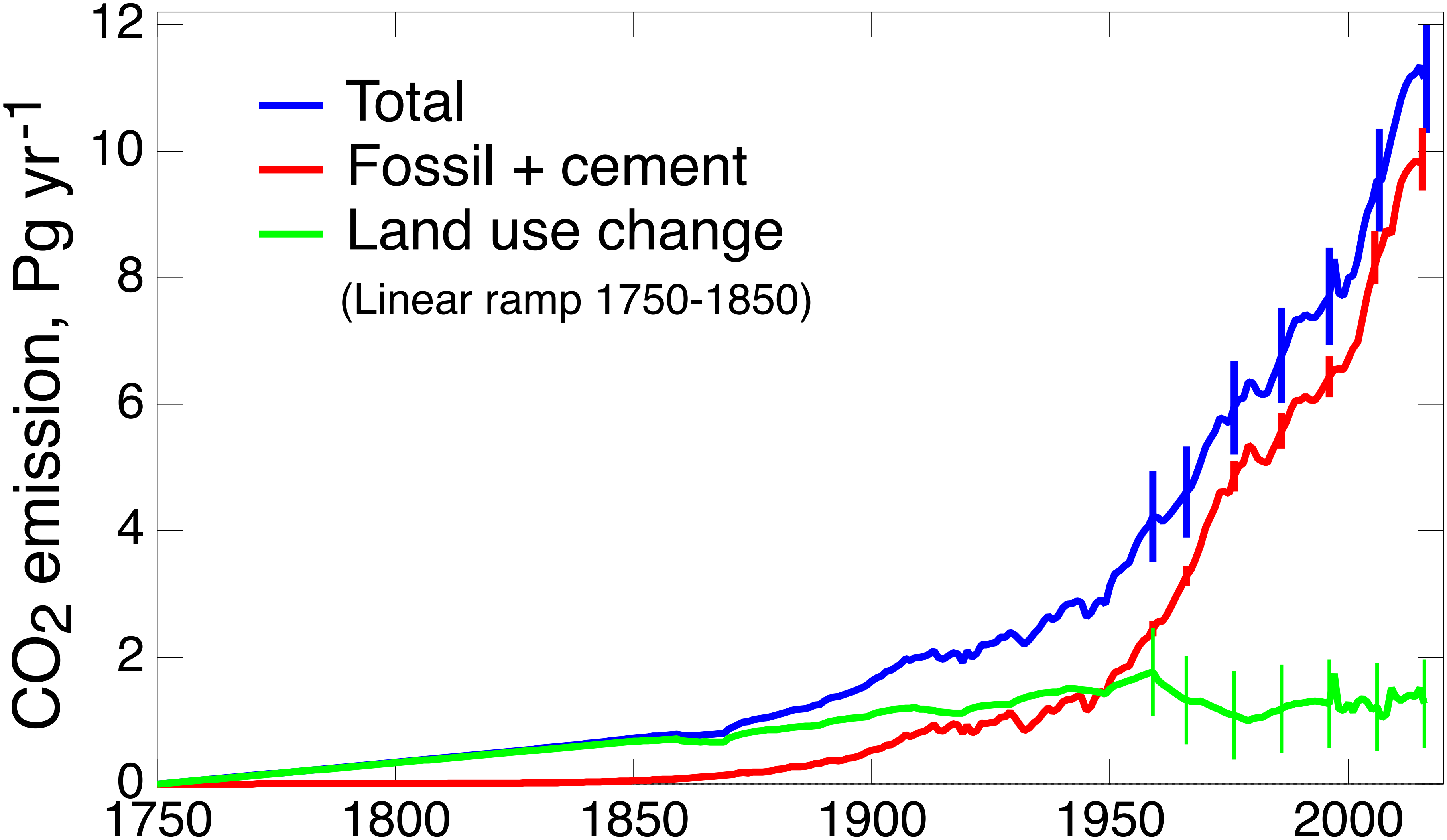
Etheridge et al., 1996
Keeling et al., 2001
Duglokencky &Tans, 2018

CARBON DIOXIDE OVER TIME



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

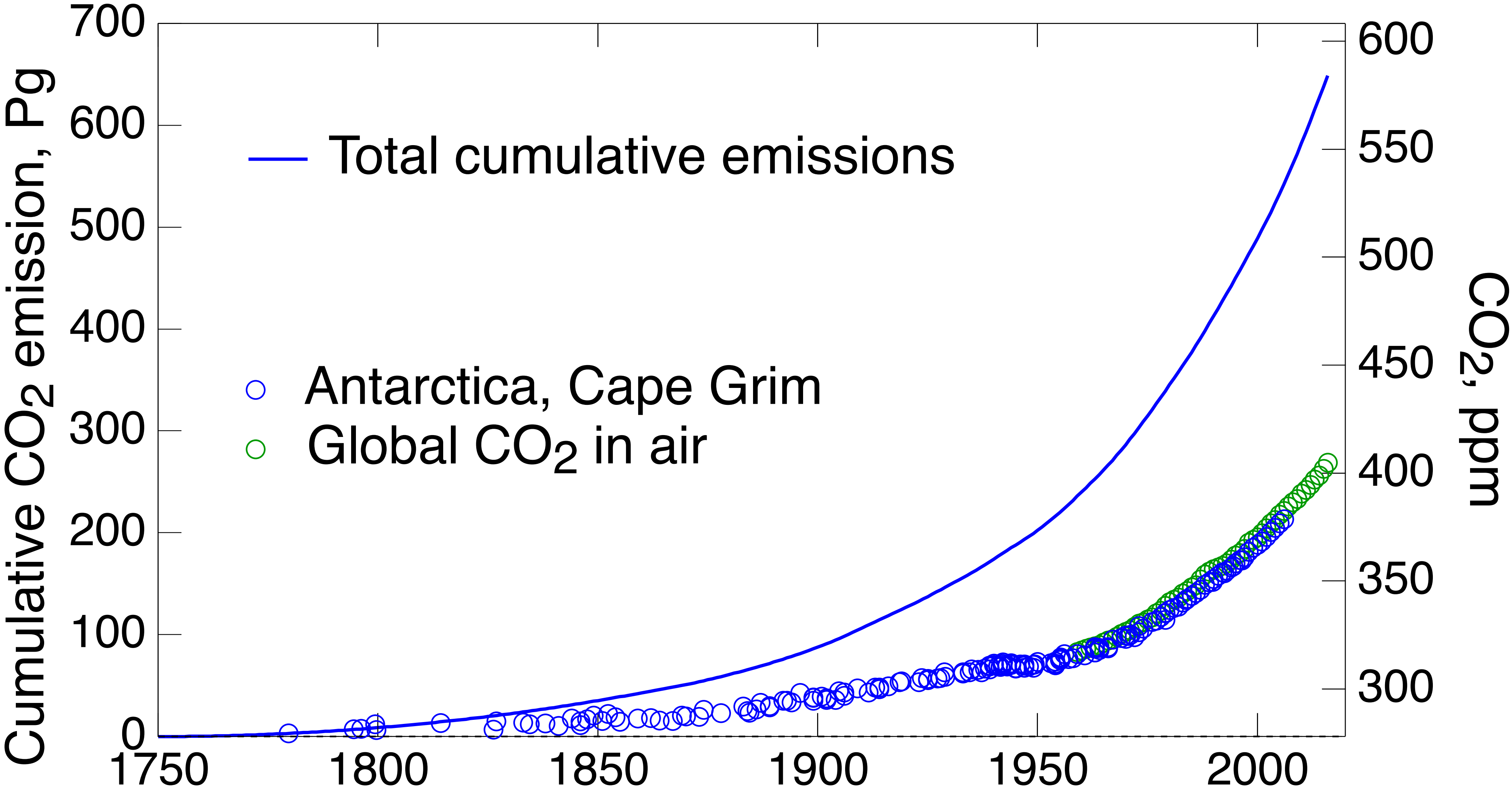
ANTHROPOGENIC CARBON DIOXIDE EMISSIONS



Boden et al., 2017

Houghton and Nassikas, 2017

CUMULATIVE ANTHROPOGENIC CO_2 EMISSIONS AND ANTHROPOGENIC ATMOSPHERIC STOCK



Nature's "subsidy" of our carbon dioxide emissions

Motivation for this study

AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres
RESEARCH ARTICLE
10.1002/2017JD028121

Unrealized Global Temperature Increase: Implications of Current Uncertainties

Stephen E. Schwartz

The "Cold Turkey" Experiment

Abrupt cessation Of Emissions

AGU PUBLICATIONS
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Unrealized Global Temperature Increase: Implications of Current Uncertainties

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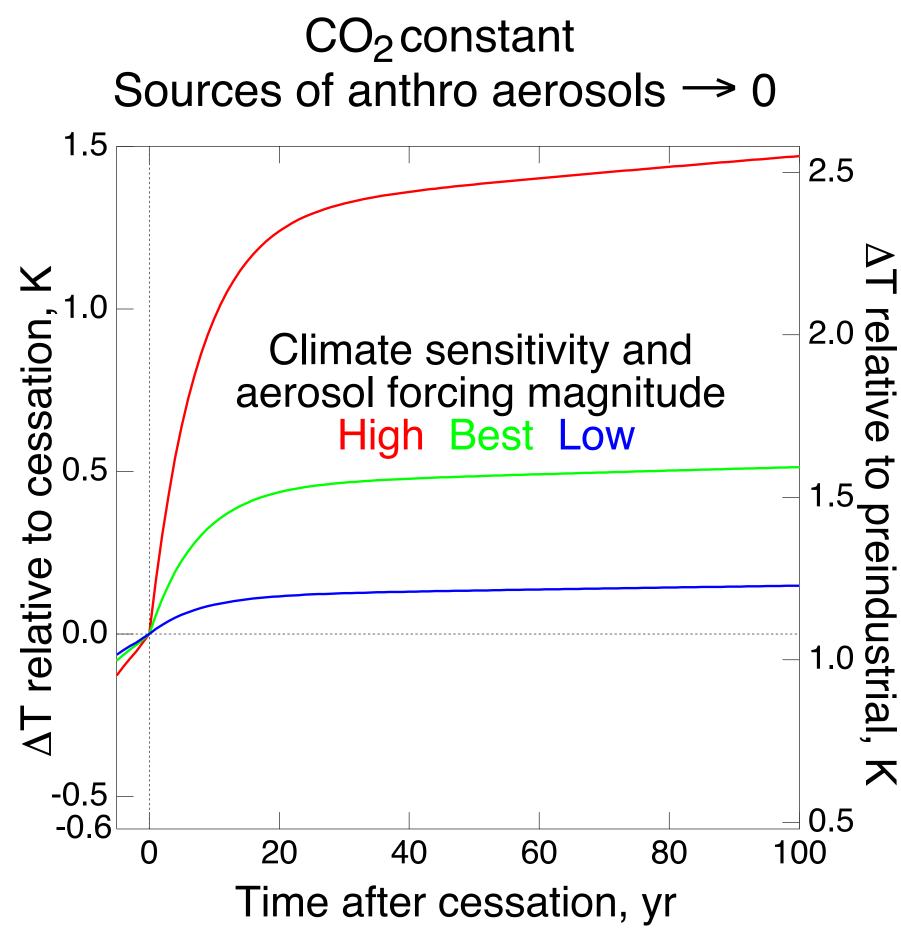
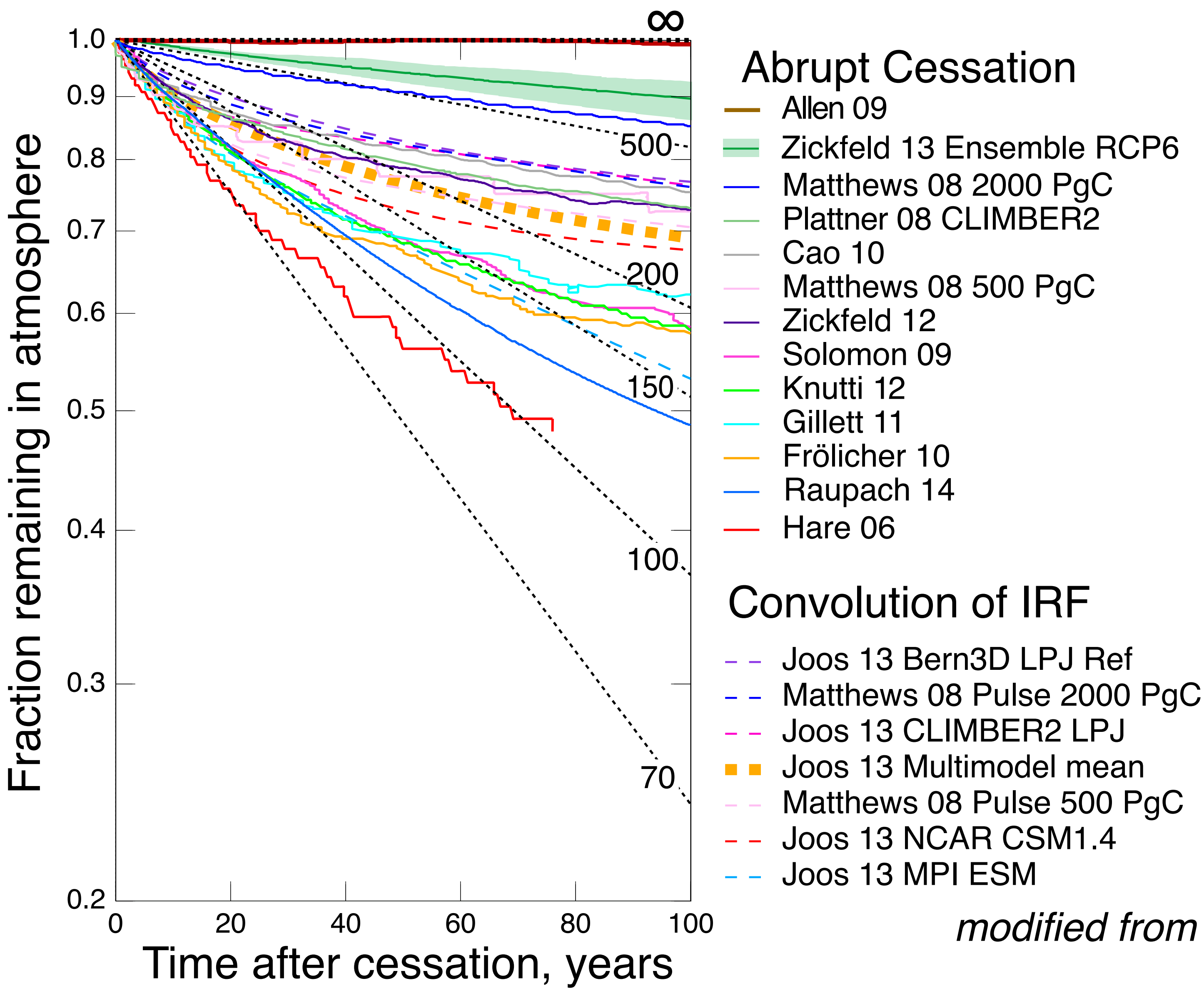


DECAY OF EXCESS ATMOSPHERIC CO_2 AFTER CESSATION OF EMISIONS

Calculated and redrawn from recent publications



modified from ses, jgr, 18

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

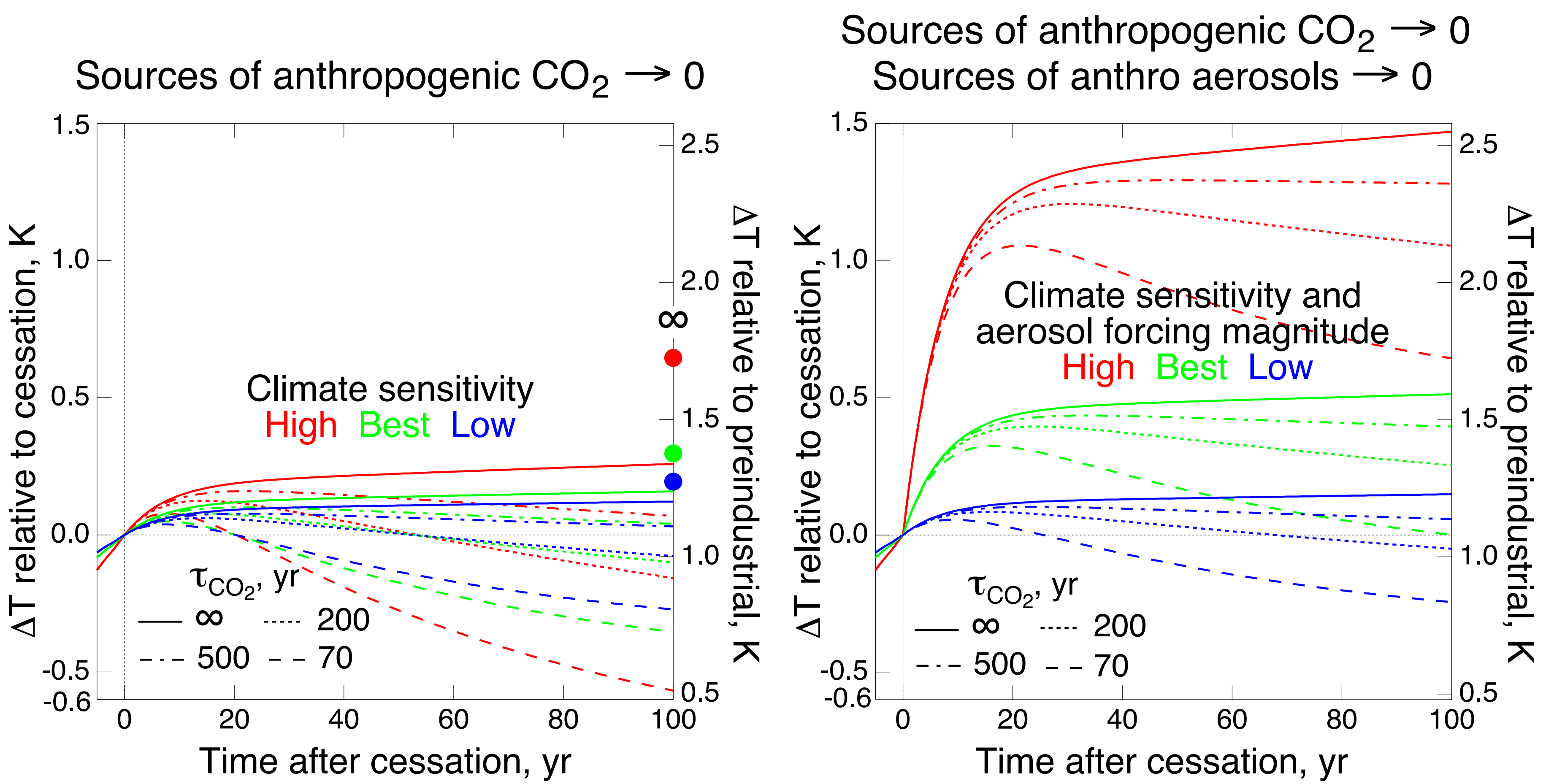
AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

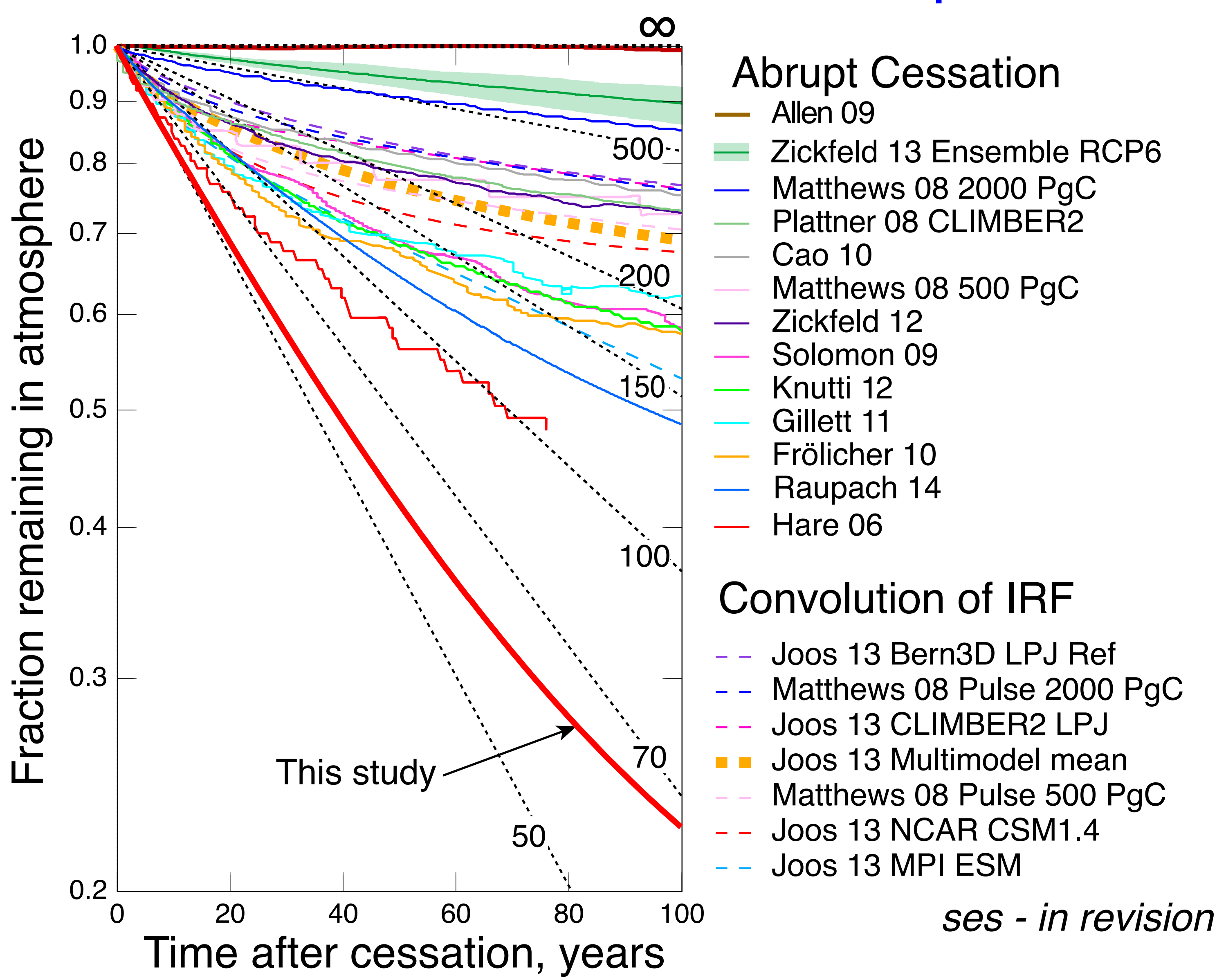
10.1002/2017JD028121

Unrealized Global Temperature Increase: Implications of Current Uncertainties

Stephen E. Schwartz



DECAY OF EXCESS ATMOSPHERIC CO_2
AFTER CESSATION OF EMISIONS
Calculated and redrawn from recent publications



ses - in revision

Lifetime (50 – 60 yr) is ***much shorter than given 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 takes 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. Requires a ***model***

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:

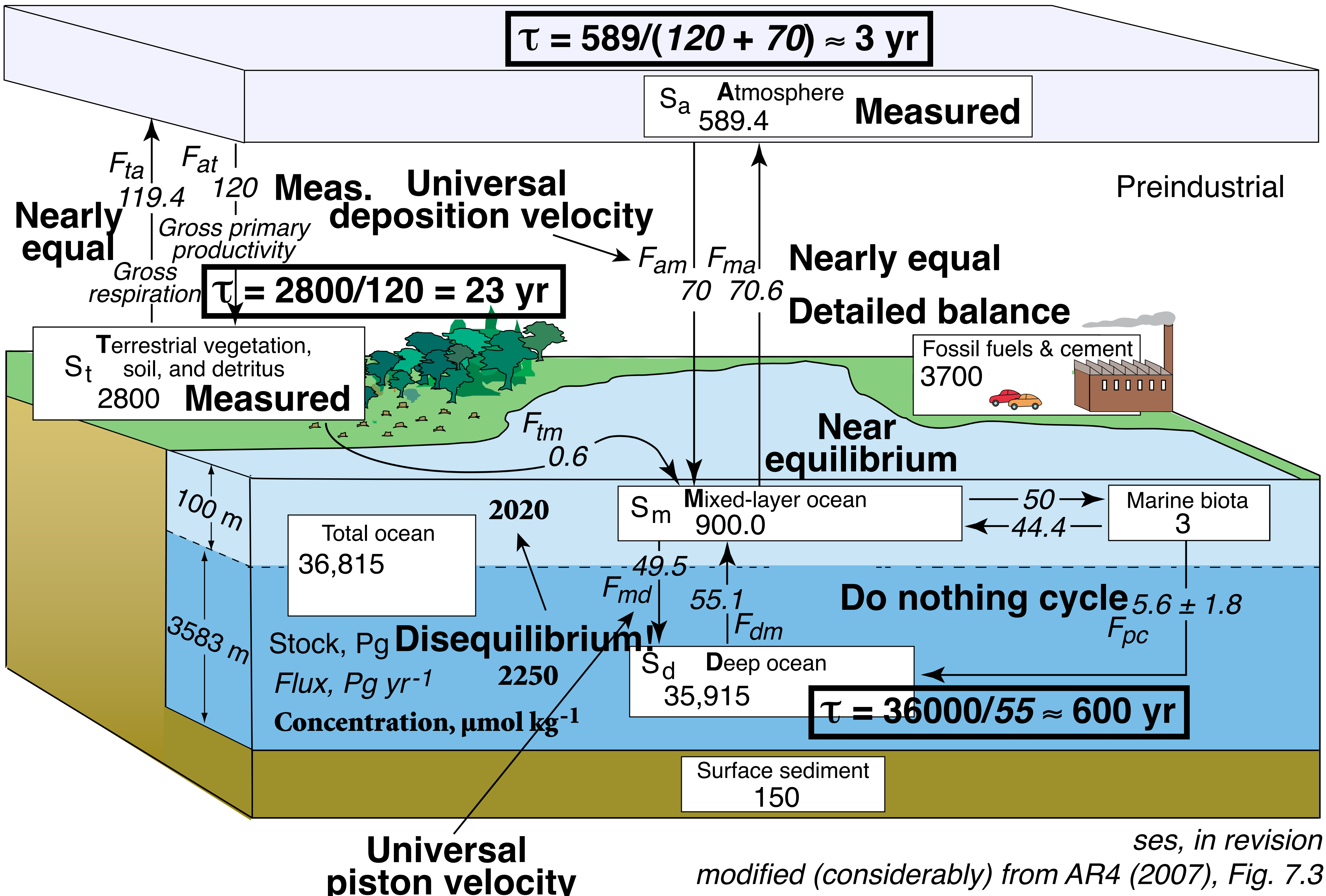
$$\tau_i^{\mathrm{adj}} = \frac{S_i}{\left(-\frac{dS_i}{dt}\right)}, \quad Q^{\mathrm{ant}} = 0$$

Requires a ***numerical model***

Observationally based Global CO_2 budget And Turnover time Of Anthropogenic CO_2

CO_2 STOCKS, *FLUXES*

Steady state



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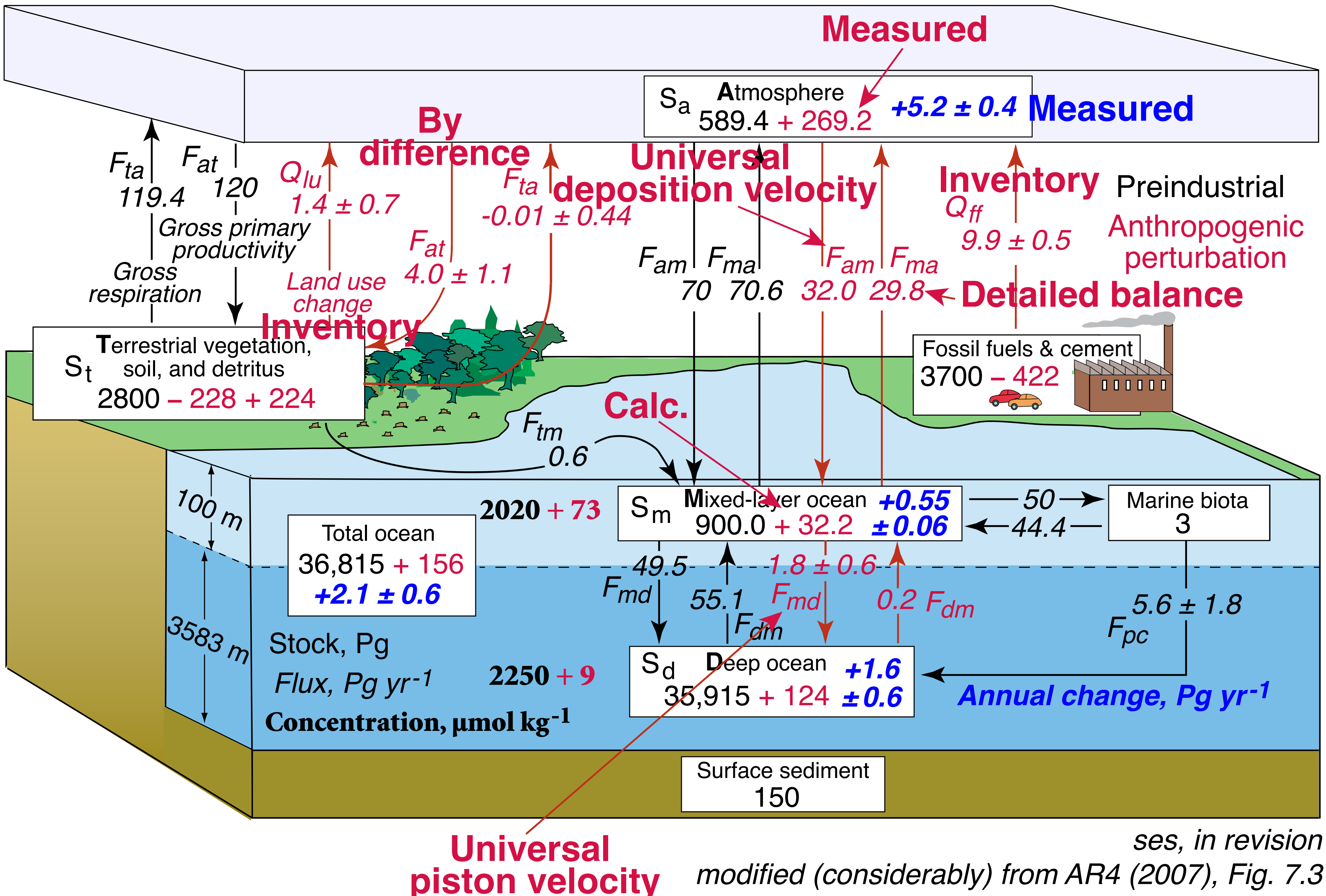
modified (considerably) from AR4 (2007), Fig. 7.3
after Sarmiento & Gruber, Phys. Today (2002)

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



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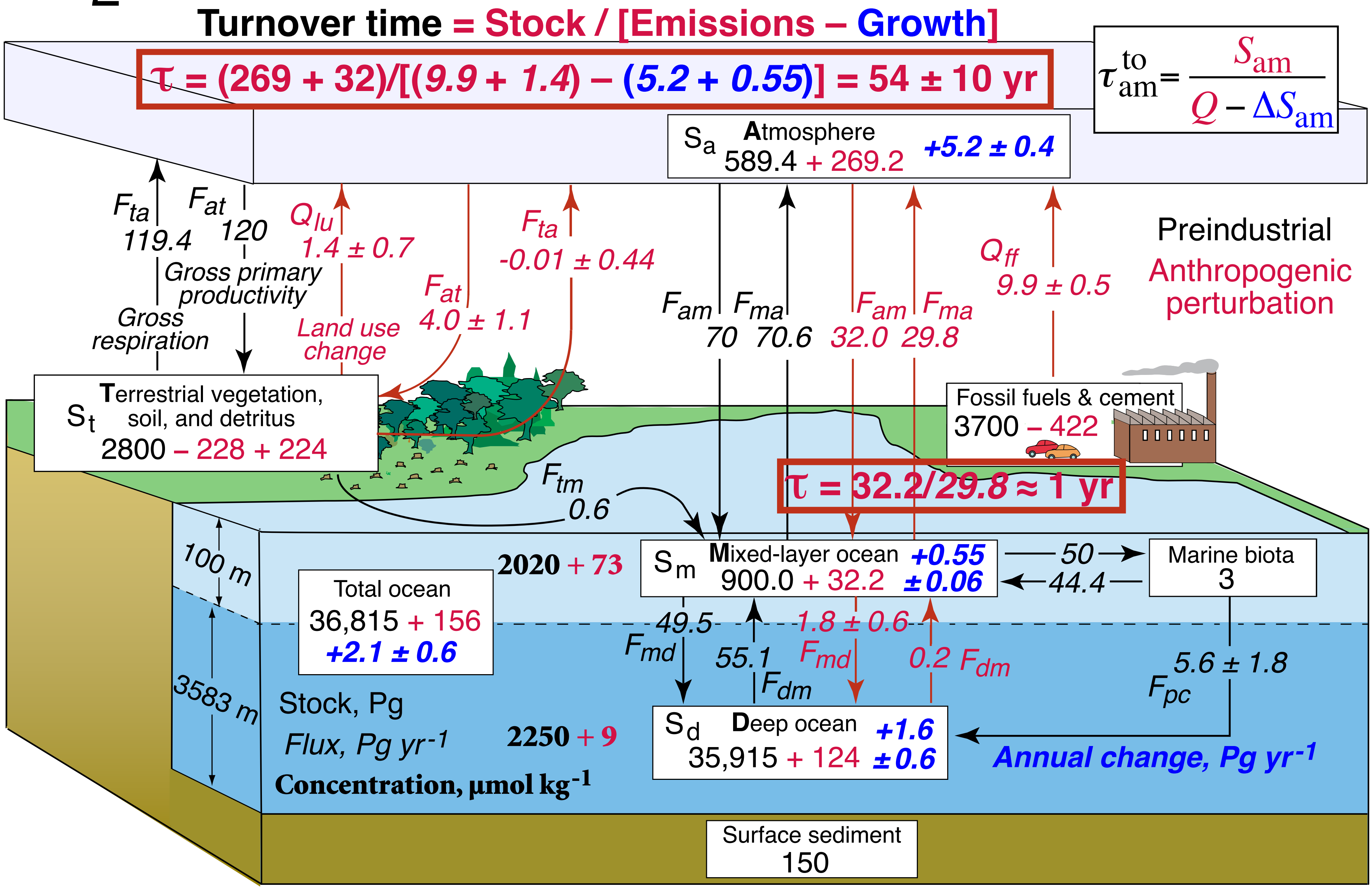
CO_2 STOCKS, *FLUXES*, AND ***ANNUAL GROWTH***



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Model for Anthropogenic CO_2

THE DIFFERENTIAL EQUATIONS

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

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

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

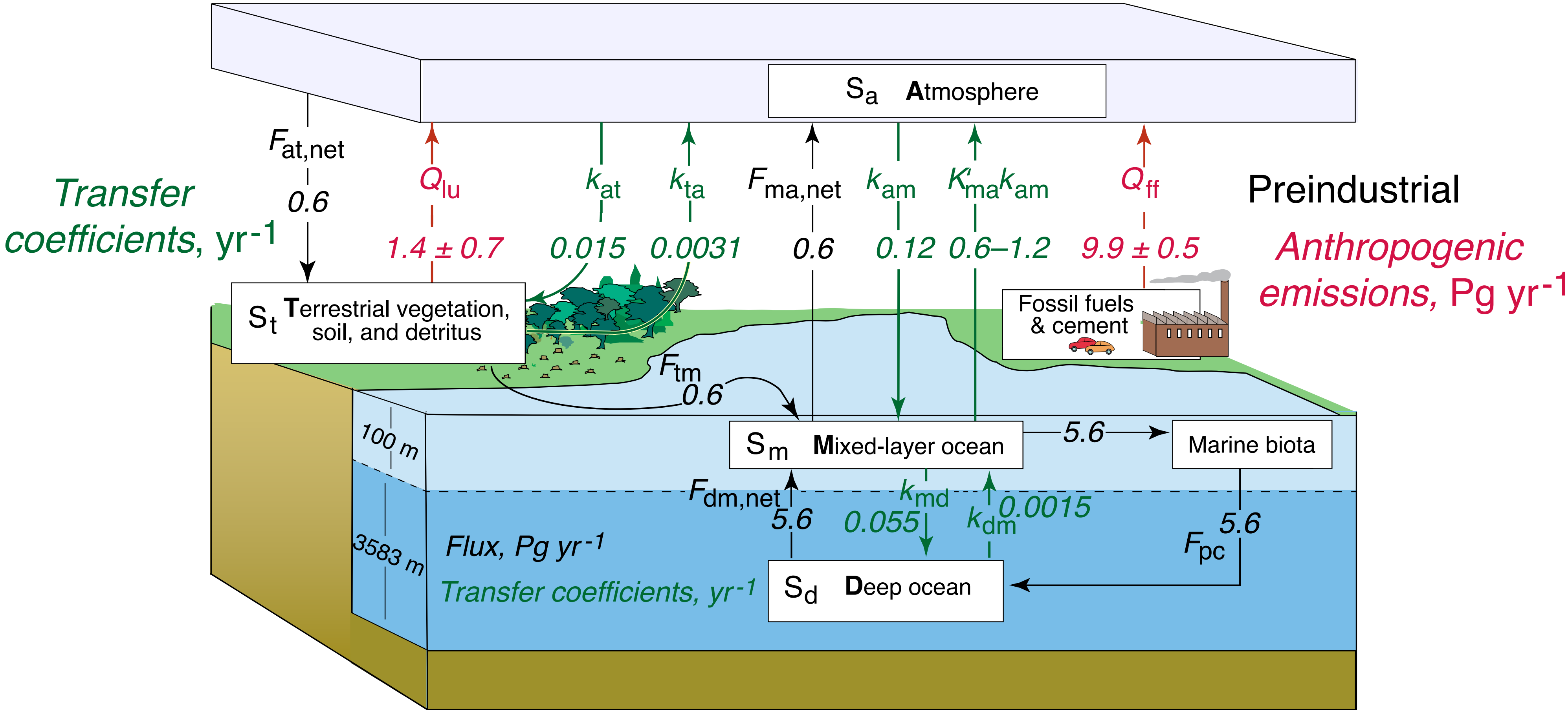
$$\frac{dS_{\mathrm{t}}}{dt} = k_{\mathrm{at}}S_{\mathrm{a}} - k_{\mathrm{ta}}S_{\mathrm{t}} - Q_{\mathrm{lu}}(t)$$

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



k_{am} = F^{pi}_{am}/S^{pi}_{a} ; 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**

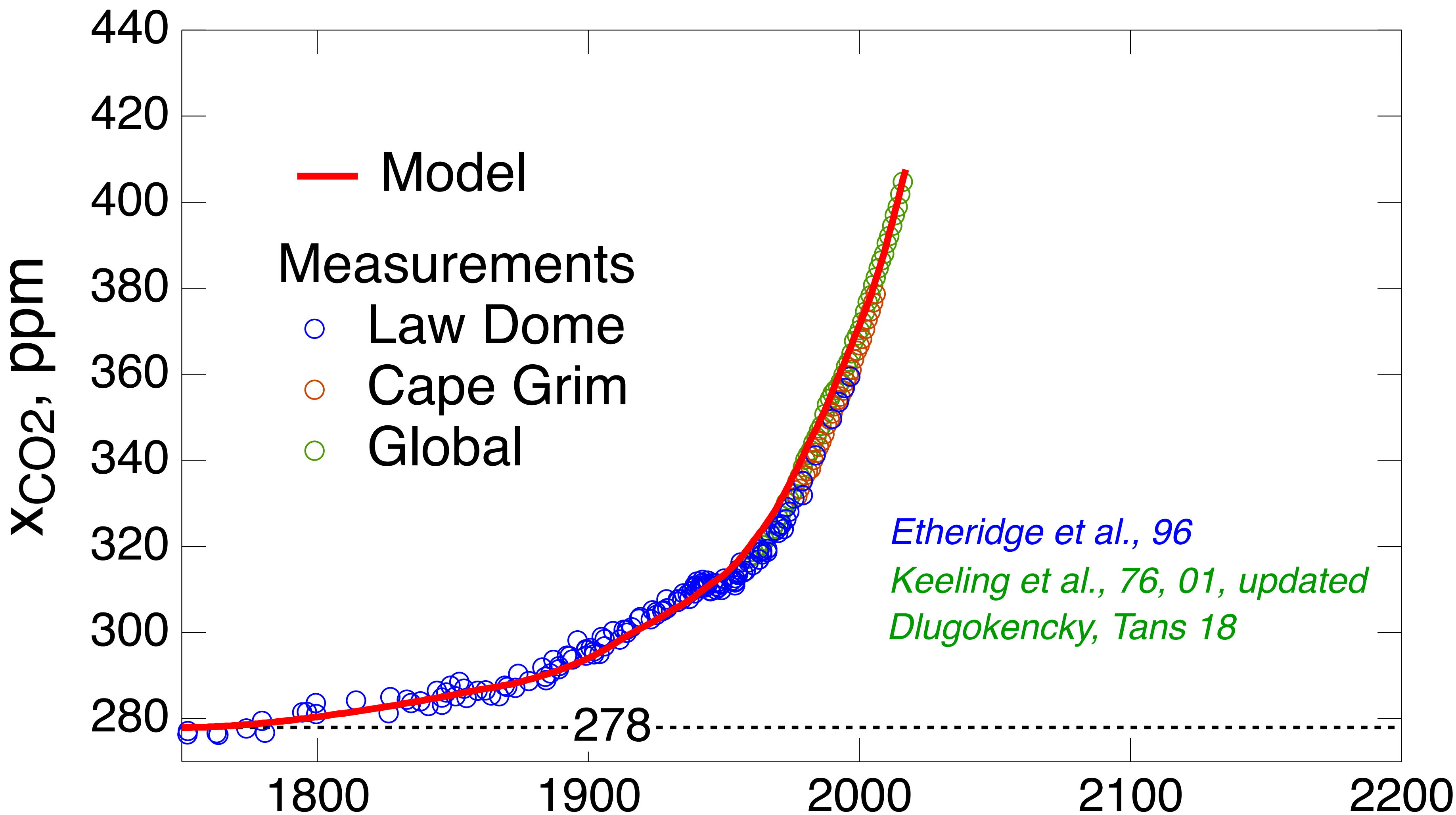
$k_{md}z_m = k_{dm}z_d = v_p$; global mean piston velocity, 5.5 m yr **Geophys ppty: from obs'd global heat uptake rate**

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

$k_{ta} = k_{at}\,(S^{pi}_a/S^{pi}_t) - F^{pi}_{tm}/S^{pi}_t$ **Preindustrial steady state**

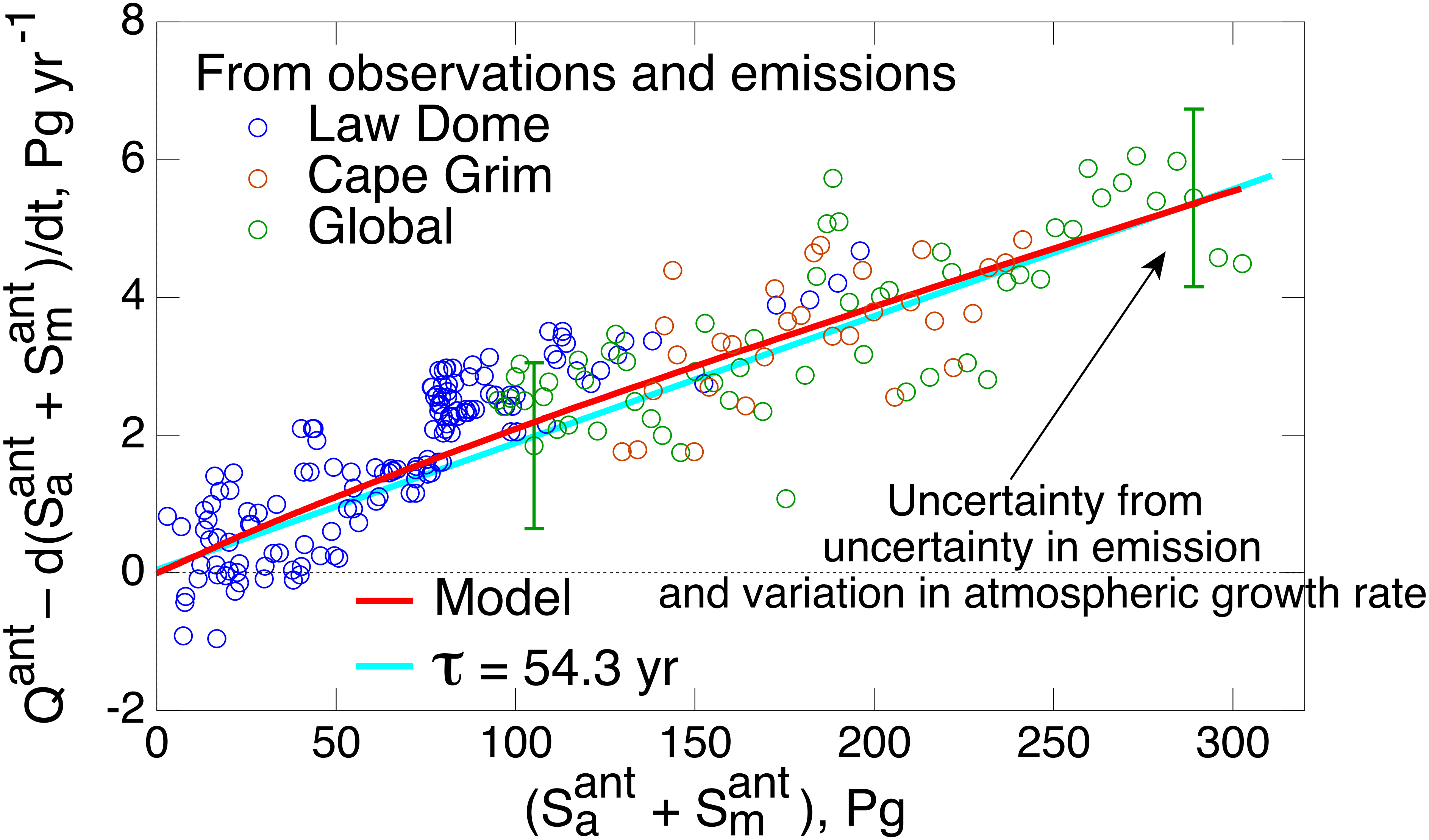
Three independent, observationally constrained parameters: k_{am}, v_p, and k_{at}

MODELED AND MEASURED CO_2 MIXING RATIO



Model accurately reproduces observed atmospheric CO_2 over the Anthropocene.

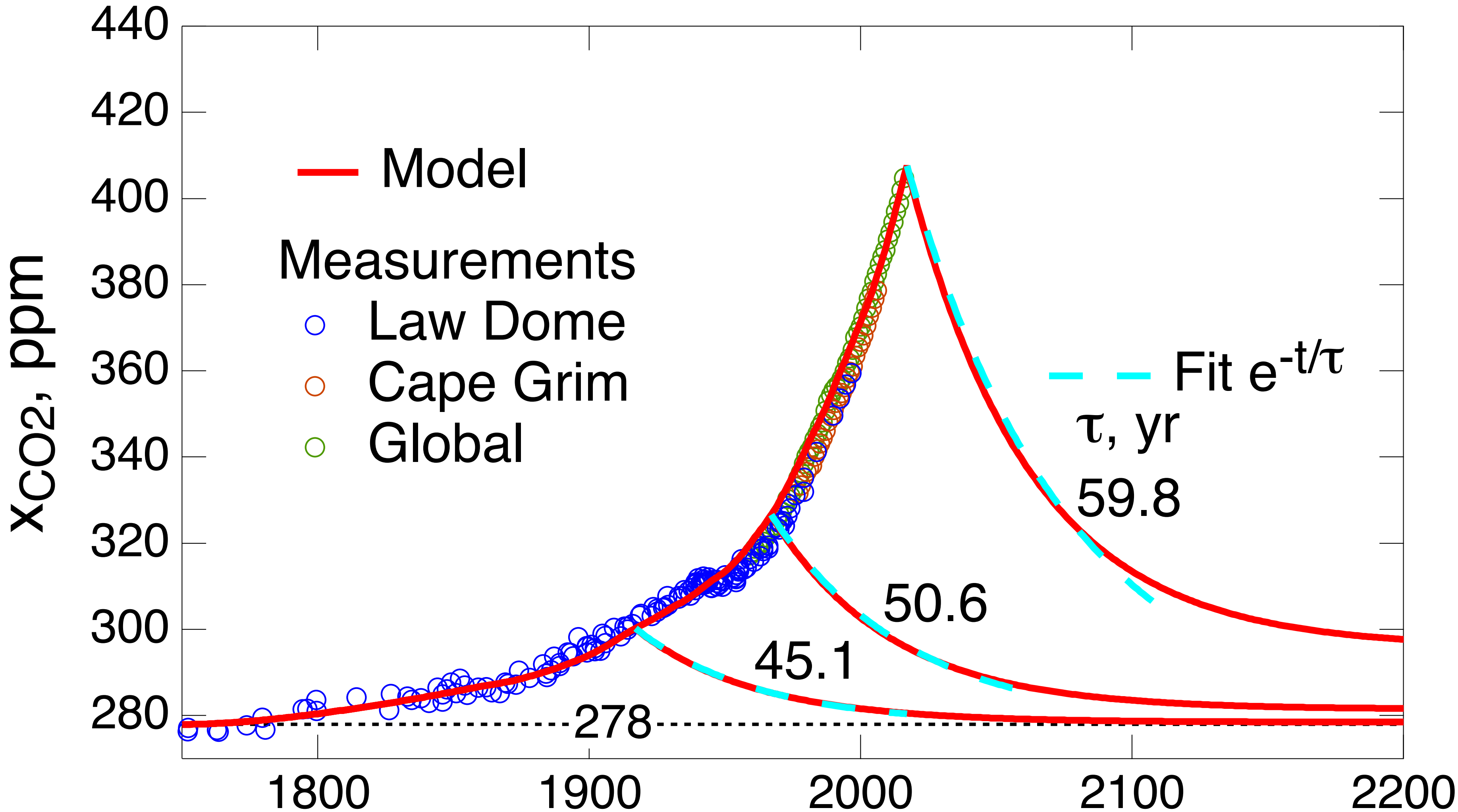
SINK RATE INTO TERRESTRIAL BIOSPHERE PLUS DEEP OCEAN



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

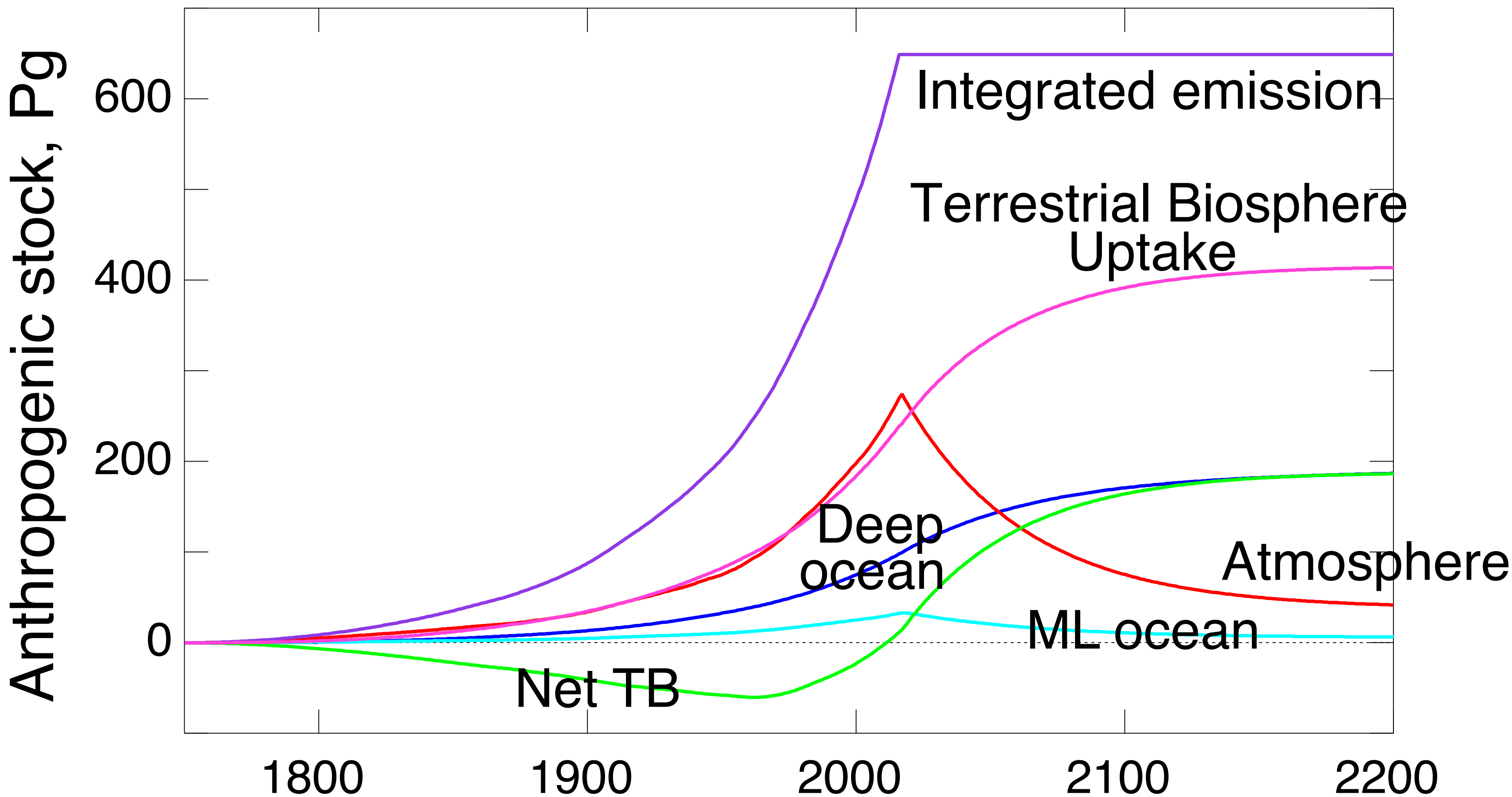


Atmospheric CO_2 decreases nearly exponentially after cessation.

Time constant is roughly the same as turnover time (54 years).

Time constant increases with increasing date of cessation.

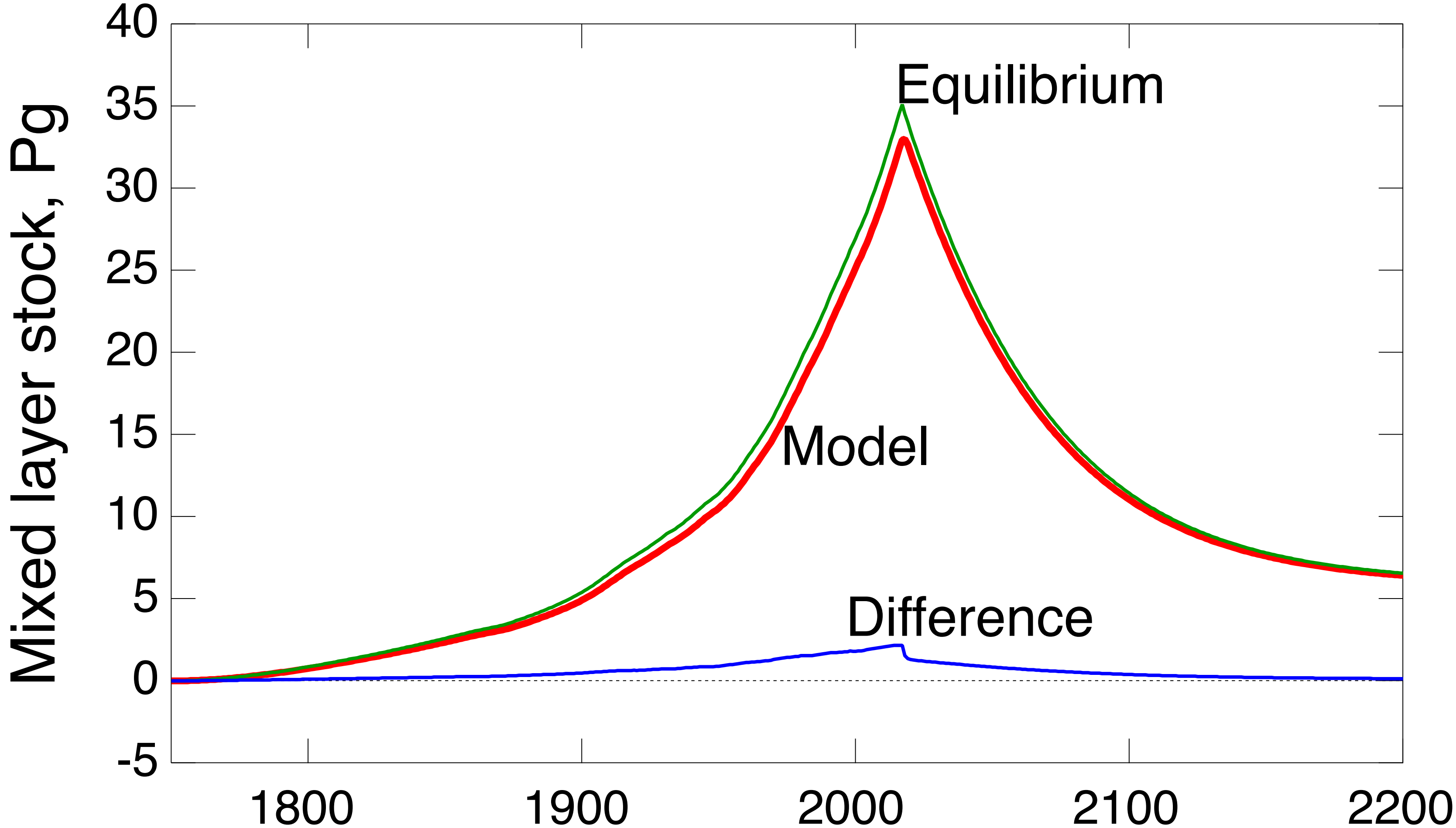
ANTHROPOGENIC STOCKS



Model allows examination of stocks in the several compartments.

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

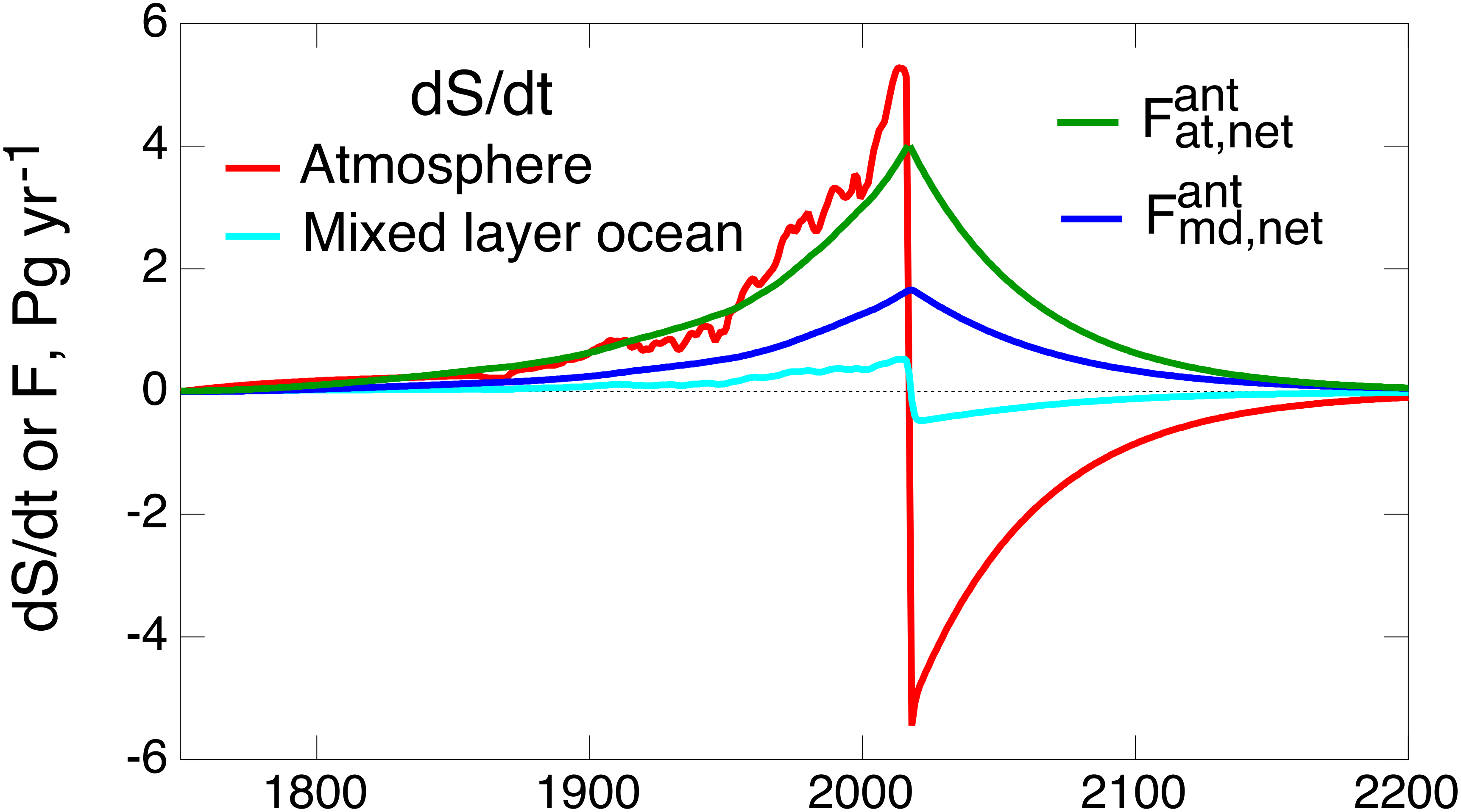
NEAR EQUILIBRIUM OF ANTHRO ATMOSPHERIC AND MIXED-LAYER STOCKS



Anthropgenic stocks in Atmosphere and ocean Mixed Layer are in ***near equilibrium***.

This argues for treating the two compartments as a ***single compartment*** to determine turnover time of anthropogenic CO_2.

FLUXES AND RATES OF CHANGE OF STOCKS



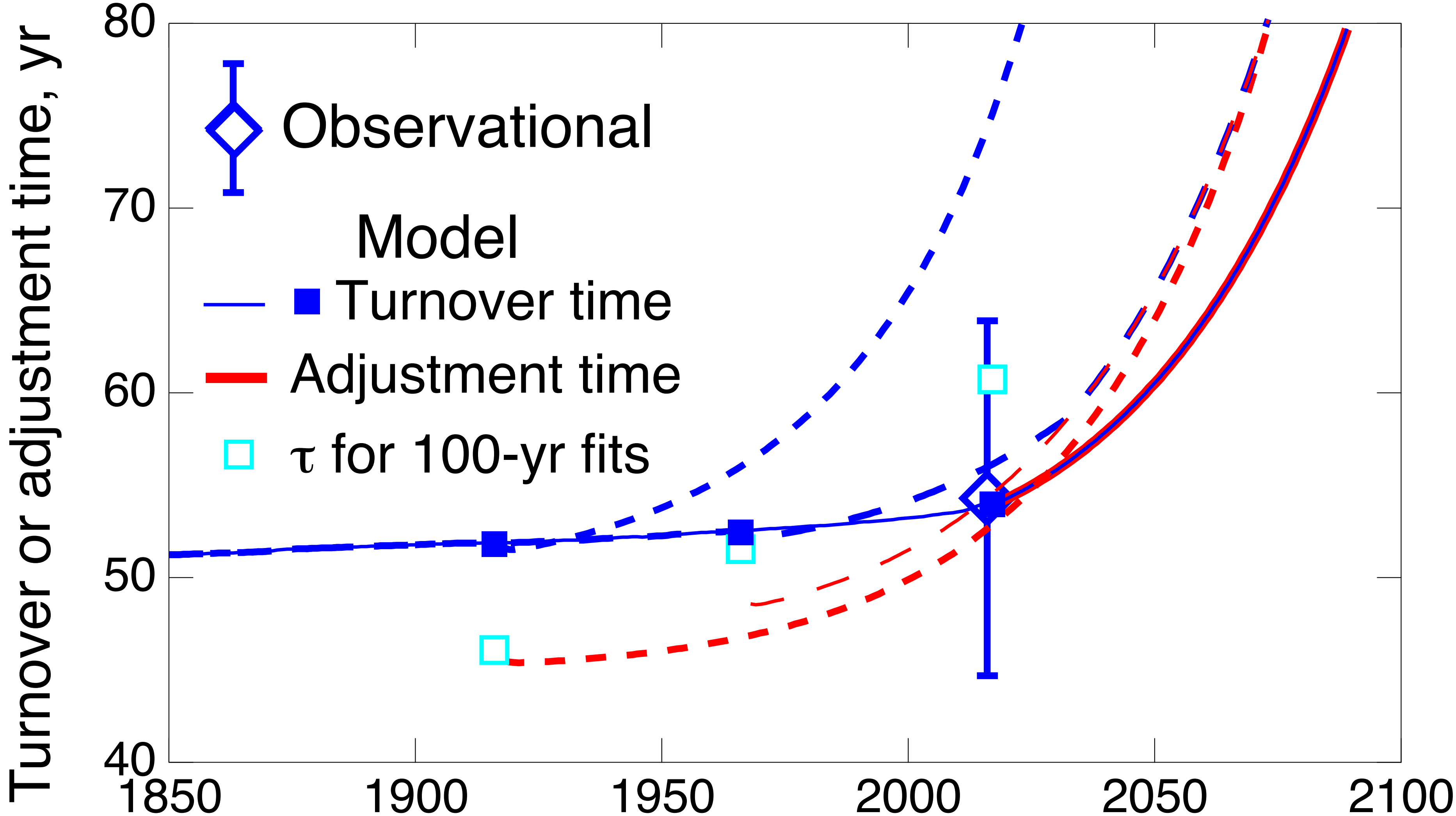
Stocks in Atmosphere and ocean Mixed Layer begin to decrease immediately on cessation (negative *dS/dt*).

Deep Ocean and Terrestrial Biosphere ***initially draw down*** $\boldsymbol{CO_2}$ ***at prior rate***.

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

Lifetime of Anthropogenic CO_2 By Multiple measures

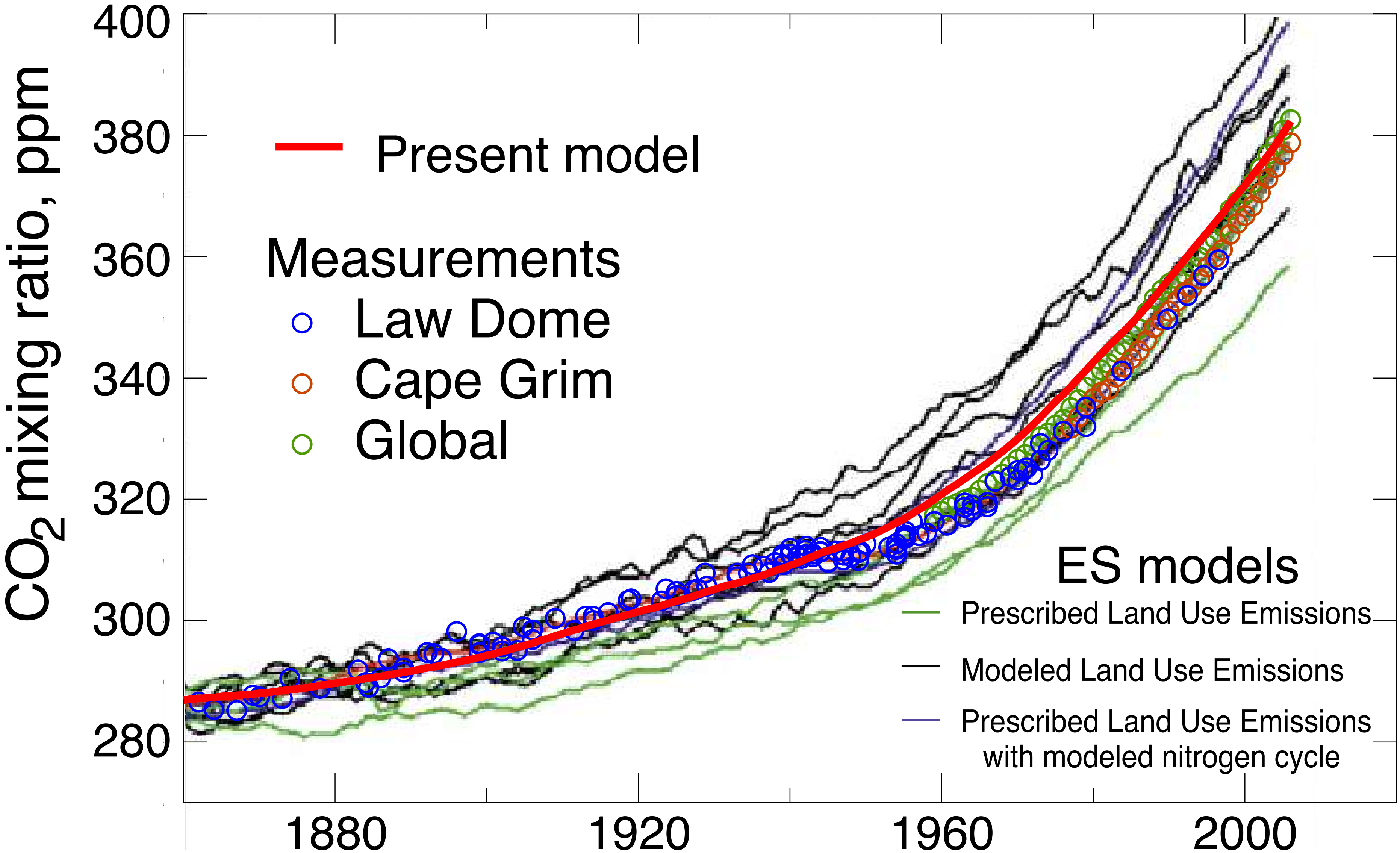
MULTIPLE MEASURES OF THE LIFETIME IN COUPLED ATMOSPHERE–MIXED-LAYER OCEAN



Lifetime of excess CO_2 is shown by multiple measures to be about 50 – 60 years.

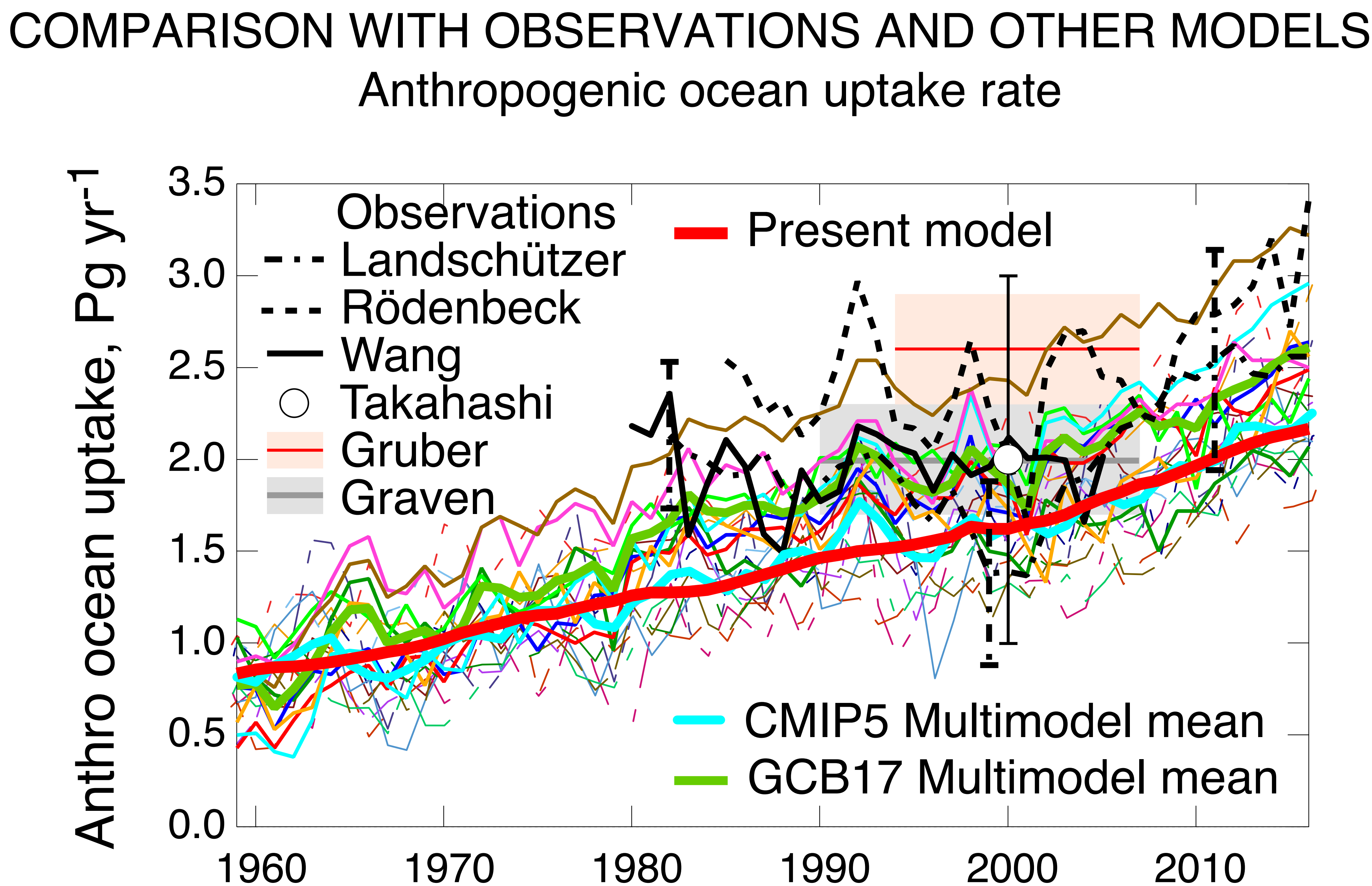
Comparisons
With Observations
And Other models

ATMOSPHERIC CO_2 MIXING RATIO



Friedlingstein et al., 2014

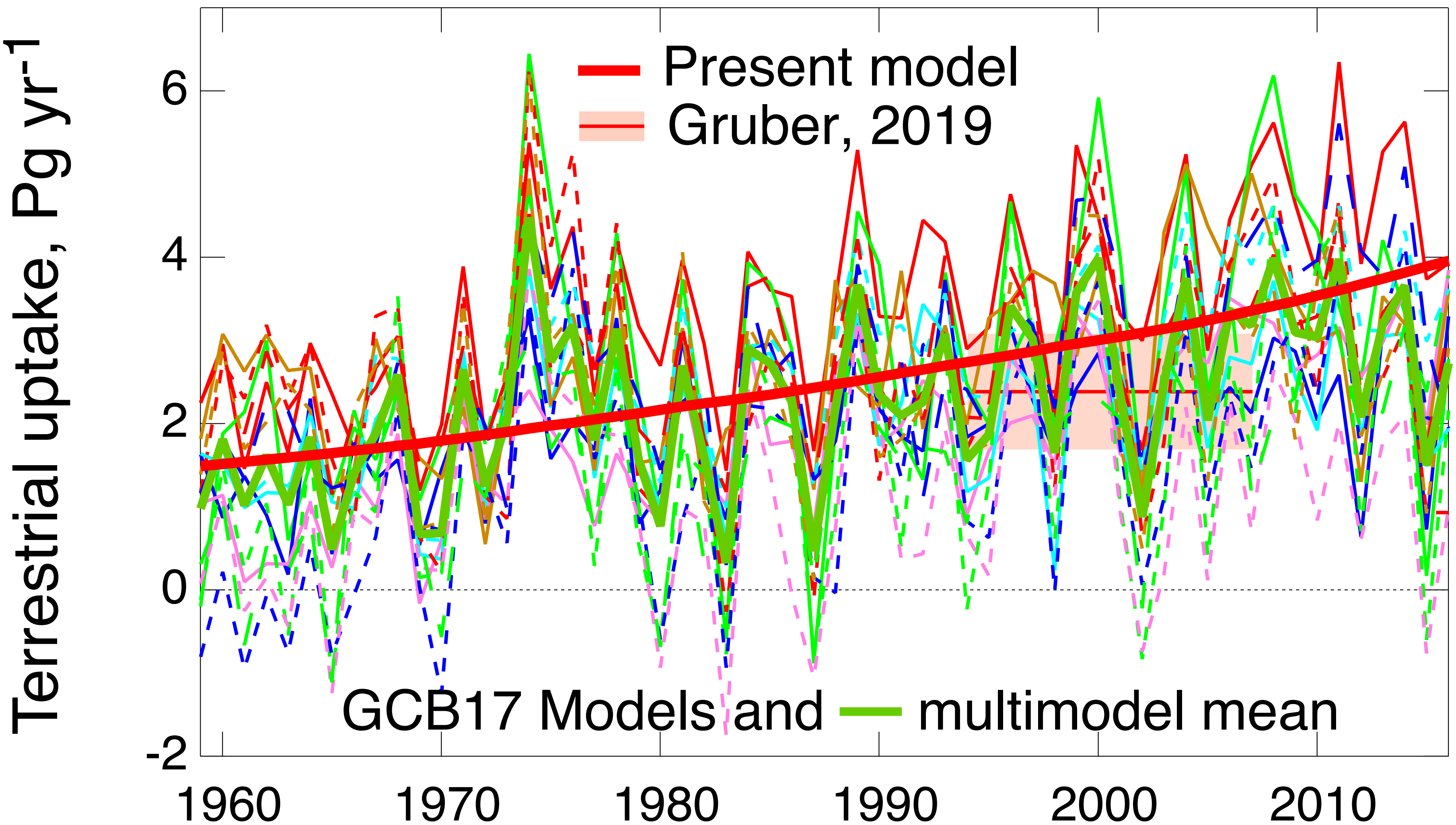
Comparison with 11 CMIP5 Earth System models.



COMPARISON WITH OBSERVATIONS AND OTHER MODELS
Anthropogenic ocean uptake rate
Anthro ocean uptake, Pg yr-1
Observations
Landschützer
Rödenbeck
Wang
Takahashi
Gruber
Graven
Present model
CMIP5 Multimodel mean
GCB17 Multimodel mean
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1960
1970
1980
1990
2000
2010

COMPARISON WITH OBSERVATIONS AND OTHER MODELS

Anthropogenic terrestrial biosphere uptake rate

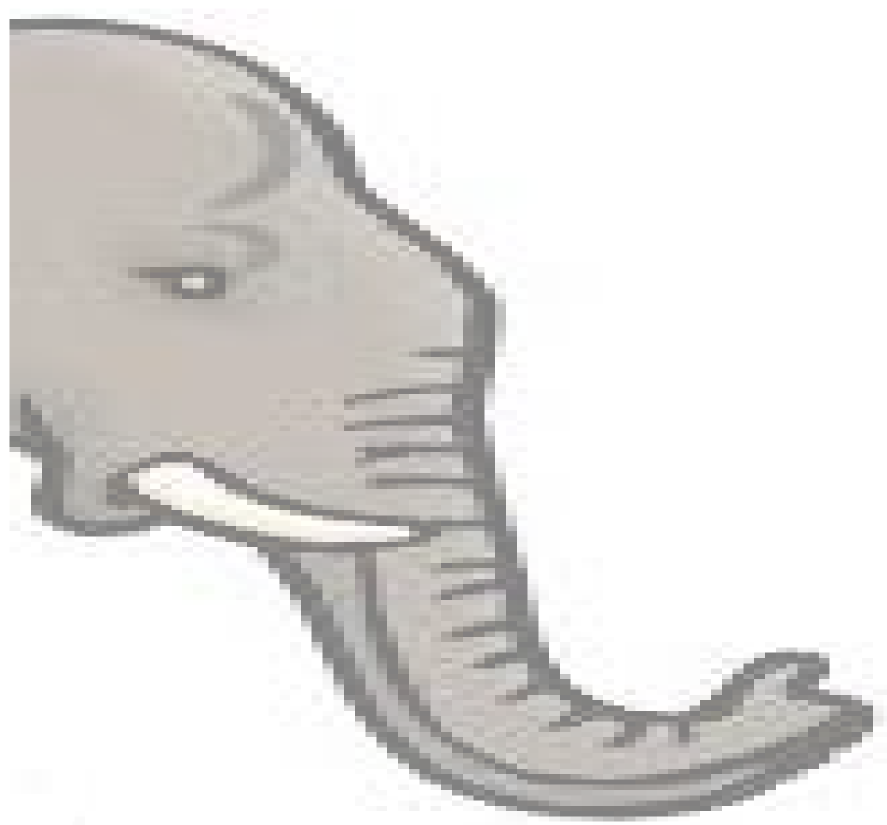


GBC17: Le Quéré et al., 2018

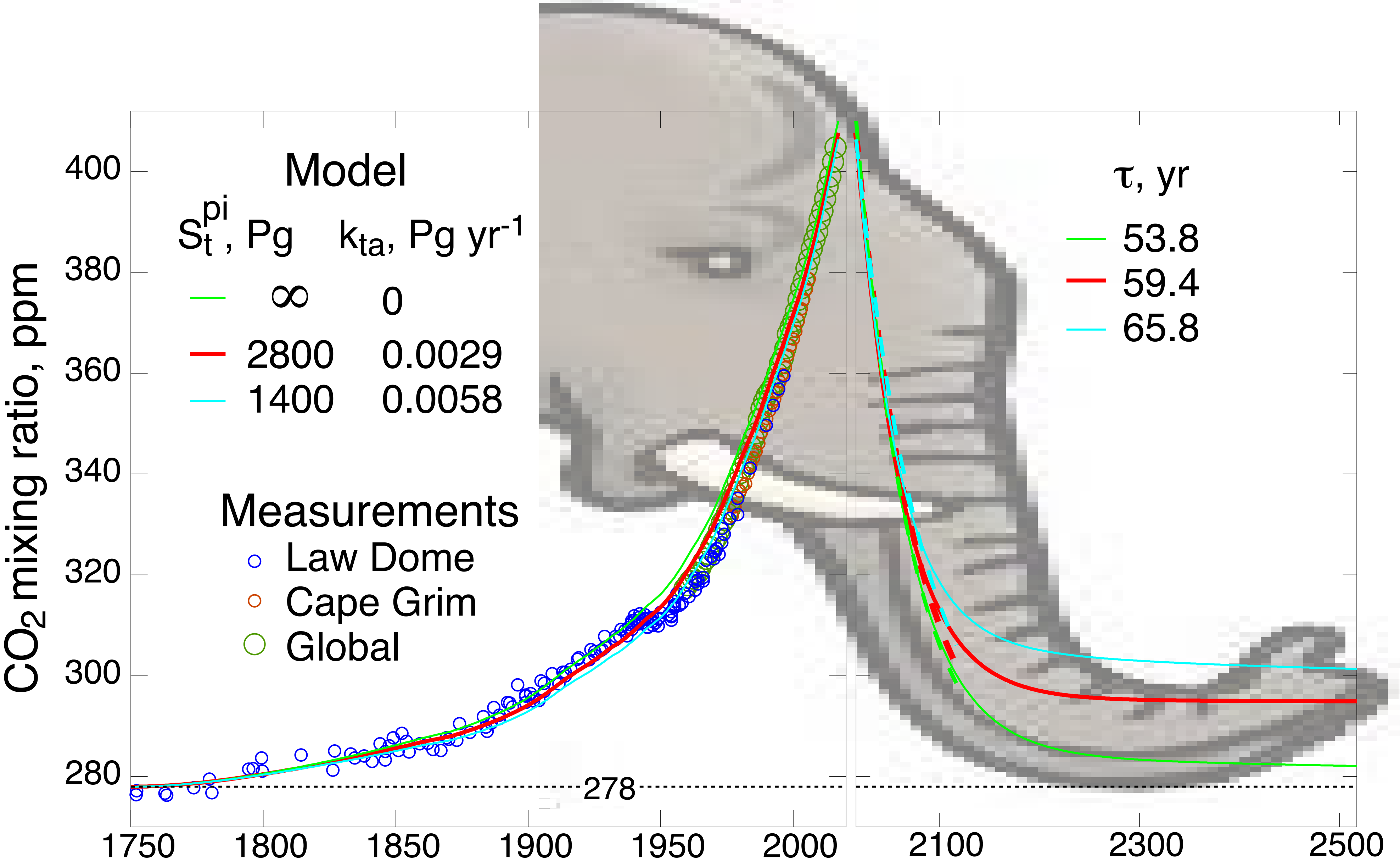
Senstivity to Terrestrial Biosphere Stock

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

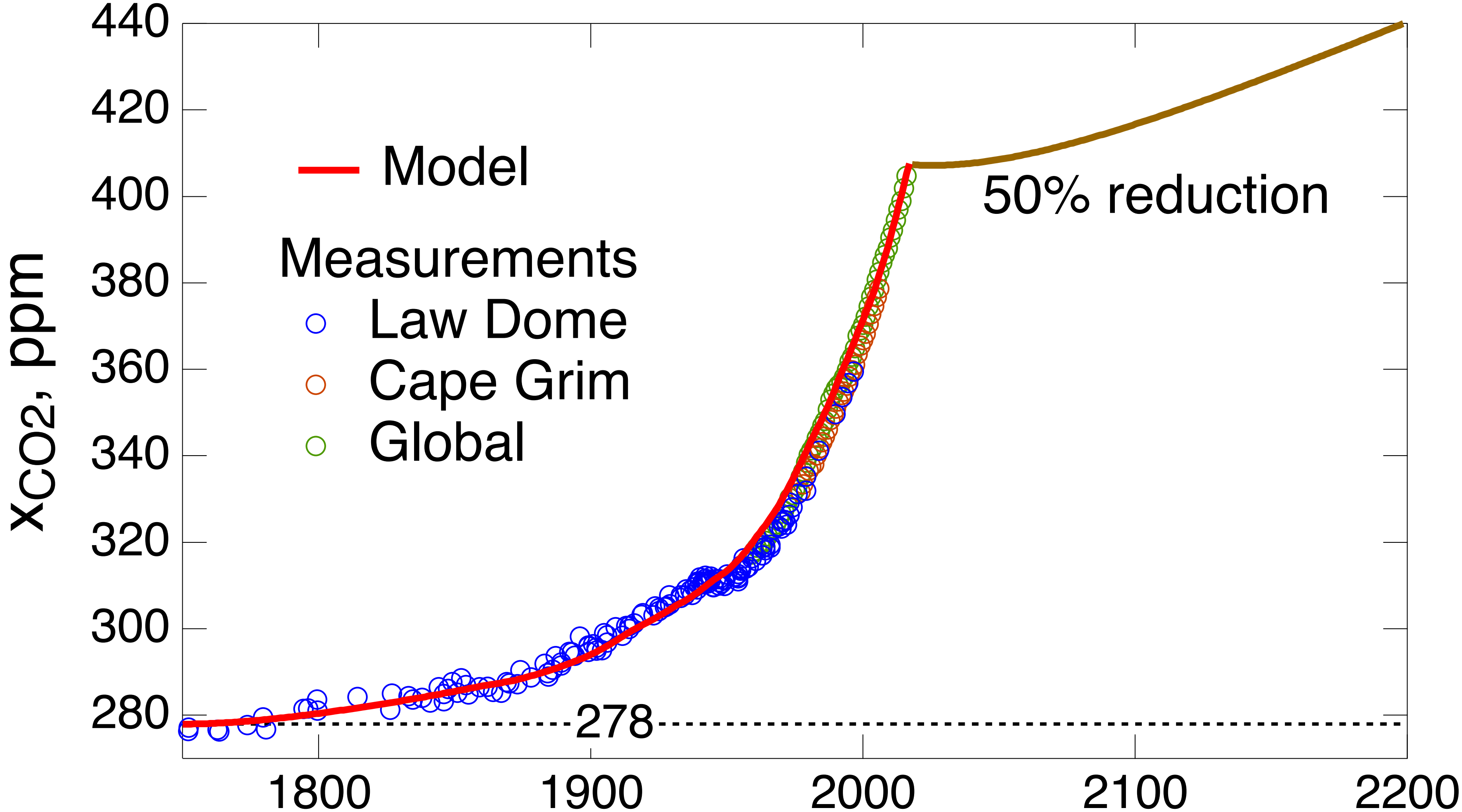


Rate and extent of decrease in atmospheric CO_2 are insensitive to ±100% change in transfer coefficient k_{ta}.

What if?

MODELED CO_2 MIXING RATIO

Abrupt 50% reduction of emissions



Near stabilization of atmospheric CO_2 could be achieved with abrupt 50% reduction of emissions.

Stabilization would be evident immediately.

CONCLUSIONS AND IMPLICATIONS

The lifetime of excess atmospheric CO_2 is found to be ***about 50 – 60 years*** by multiple measures.

This lifetime is ***much shorter than most present estimates***.

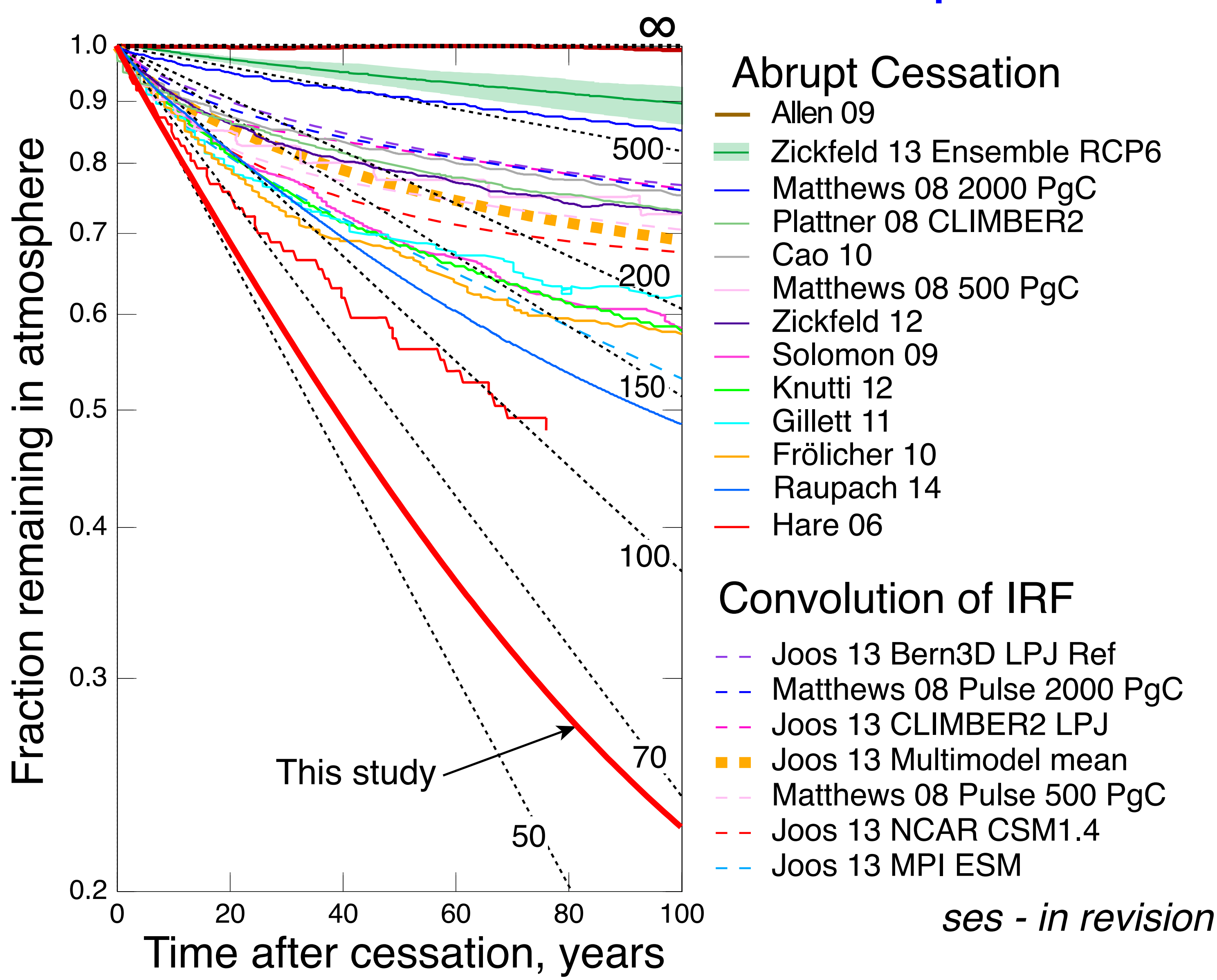
Atmospheric CO_2 could be ***stabilized*** at its present value by halving current emissions.

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

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

DECAY OF EXCESS ATMOSPHERIC CO_2 AFTER CESSATION OF EMISIONS

Calculated and redrawn from recent publications



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