STABILIZING CARBON DIOXIDE

U.S. DEPARTMENT OF ENERGY

Office of Science

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BROOKHAVEN NATIONAL LABORATORY

MOTIVATION

Carbon dioxide is the major anthropogenic greenhouse gas, derived mainly from fossil fuel combustion for energy production.

How much would global CO_2 emissions need to be reduced to stabilize atmospheric CO_2 over the next century?

At present CO_2 response to hypothetical emission changes is highly uncertain, based on multiple carbon cycle models.

This uncertainty greatly limits planning of energy futures and design of strategies to achieve proposed global temperature targets.

APPROACH

Analyze the CO_2 budget: Stocks in four compartments – Atmosphere, Mixed-Layer ocean, Deep Ocean, Terrestrial Biosphere – and fluxes between these compartments, constrained by observations and pertinent physical laws.

Determine transfer coefficients obtained from the budget.

Represent the CO_2 budget by differential equations in stocks of the compartments

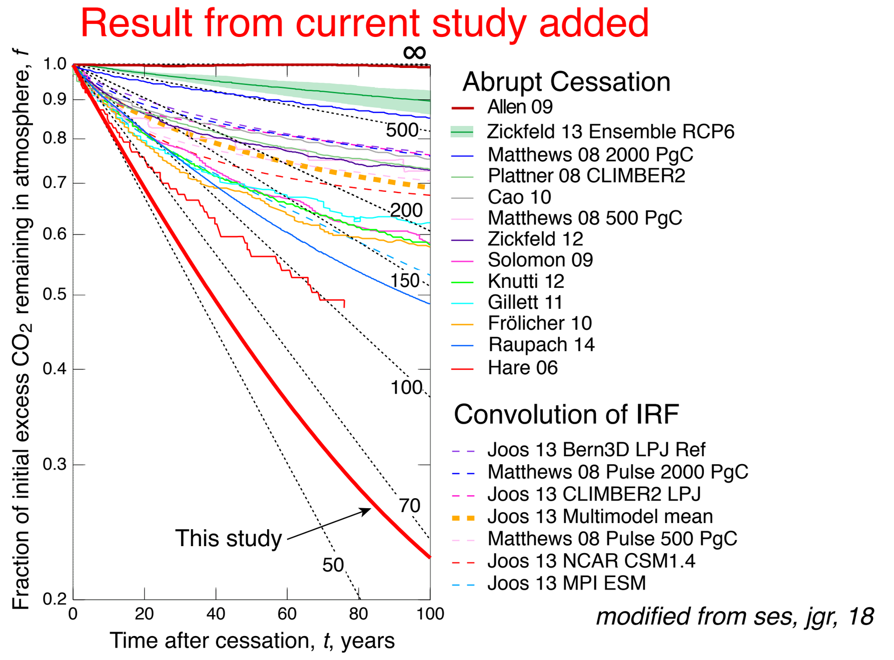
Examine observables, especially CO_2 mixing ratio, over the Anthropocene thus far and for hypothetical future emissions.

BACKGROUND

DECAY OF EXCESS ATMOSPHERIC CO_2 AFTER ABRUPT CESSATION OF EMISSIONS

Calculated and redrawn from recent publications

Result from current study added



Current estimates vary by an order of magnitude!

Lifetime (50 – 65 yr) is much shorter than in prior studies.

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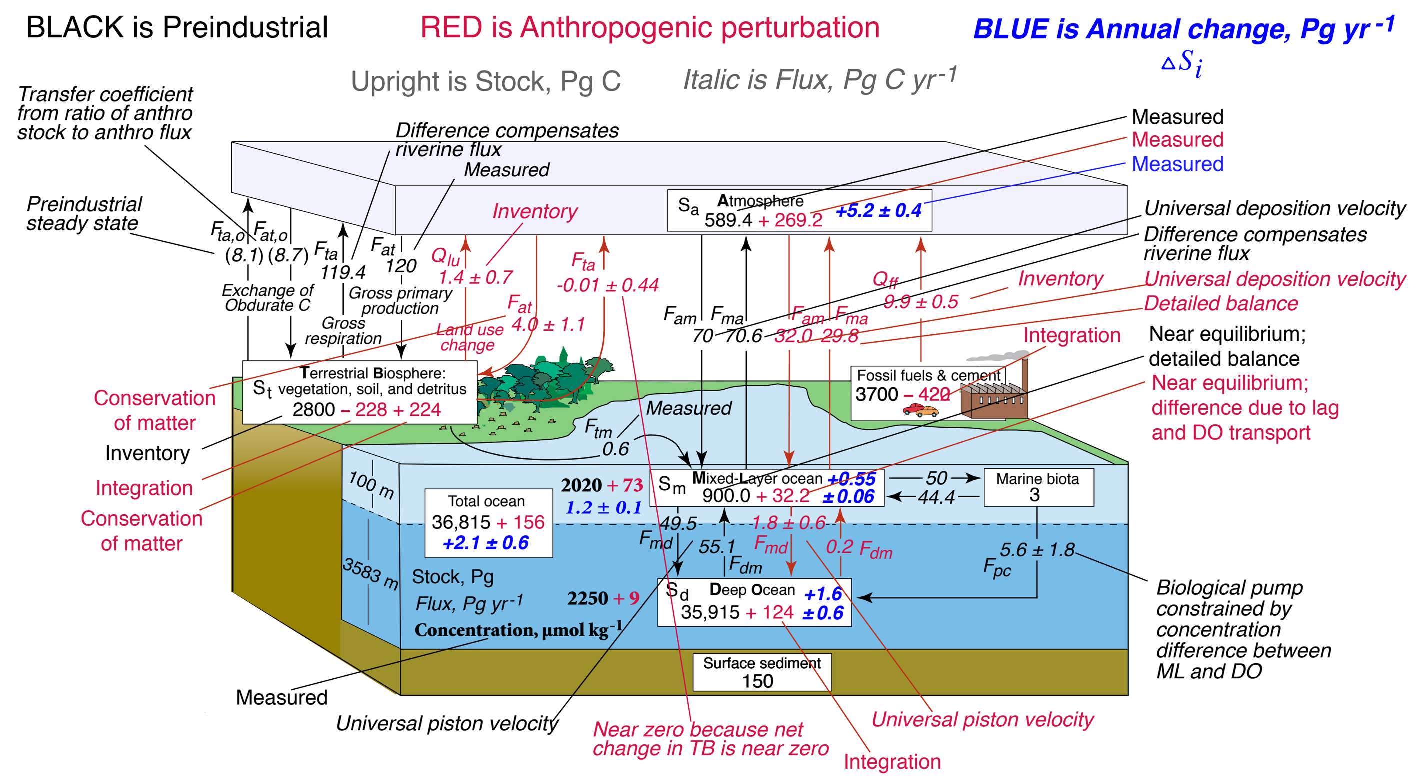
REVISED CO_2 BUDGET

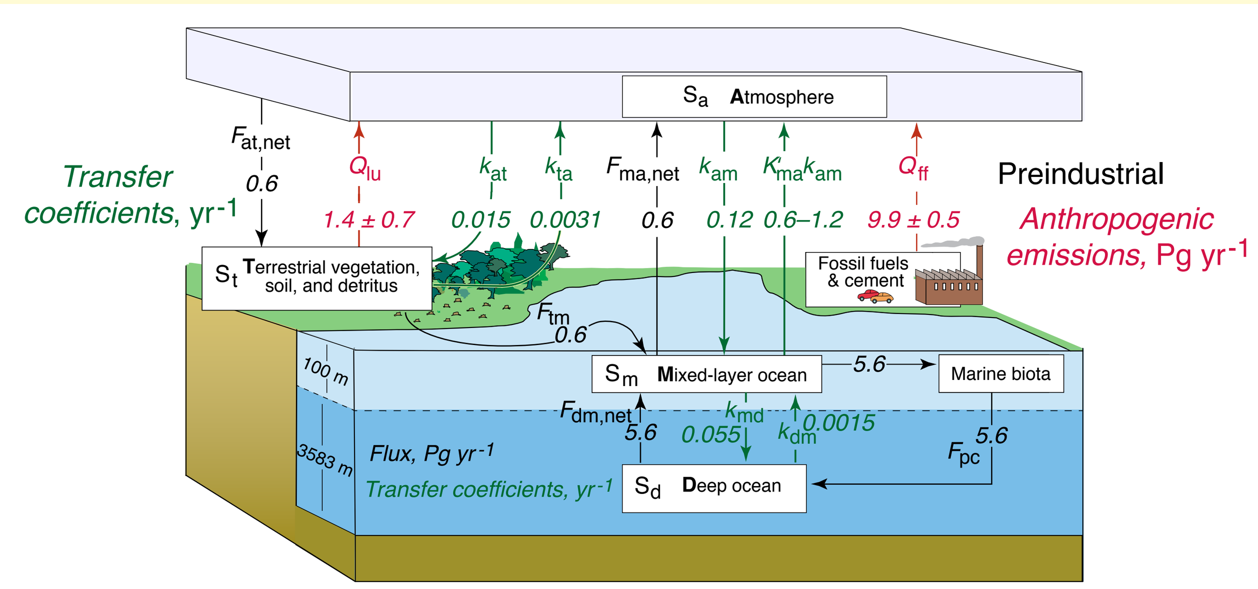


Based on (and substantially modified from) AR4 (Figure 7.3) after Sarmiento and Gruber (Phys. Today, 2002)

Every number comes from somewhere: Measurement, universal transfer coefficients, equilibria, steady state, detailed balance, conservation of matter.

About half of anthropogenic emitted CO_2 is taken up by long term reservoirs: Deep Ocean and Terrestrial Biosphere.

TRANSFER COEFFICIENTS



$\boxed{k_{am}} = F^{pi}_{am} / S^{pi}_a$; 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**

$k_{md}z_m = k_{dm}z_d = \boxed{v_p}$; 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**

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

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

IMPLICATIONS OF THE BUDGET

TURNOVER TIME OF ANTHROPOGENIC CO_2

Ratio of Stock to Net Flux out

Stocks in Atmosphere and Mixed-layer ocean are in near equilibrium and treated as a single stock.

$$\tau_i^{to} = \frac{S_i}{\sum_j F_{ij}^{net}} = \frac{S_i}{Q - \Delta S_i} = \frac{S_a^{ant} + S_m^{ant}}{Q_{ant} - (\Delta S_a^{ant} + \Delta S_m^{ant})}$$

$$S_a^{ant} + S_m^{ant} = (269.2 + 32.2)\ \text{Pg} = 301.4\ \text{Pg}$$

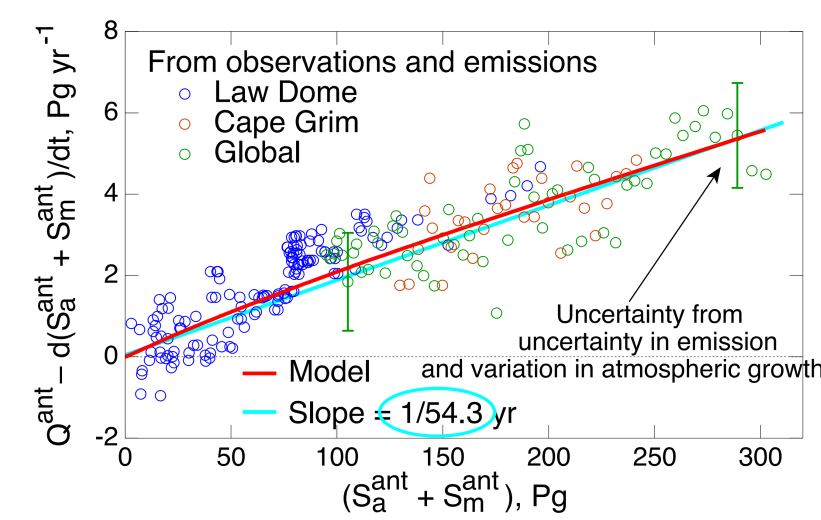
$$Q_{ant} = Q_{ff} + Q_{lu} = (9.9 + 1.4)\ \text{Pg yr}^{-1} = 11.3\ \text{Pg yr}^{-1}$$

$$\Delta S_a^{ant} + \Delta S_m^{ant} = (5.2 + 0.55)\ \text{Pg yr}^{-1} = 5.75\ \text{Pg yr}^{-1}$$

$$\tau_{am}^{to} = 301.4\ \text{Pg} / 5.75\ \text{Pg yr}^{-1} = 54.3\ \text{yr}$$

Turnover time is a robust measure of the lifetime of excess CO_2 over the Anthropocene.

SINK RATE INTO TERRESTRIAL BIOSPHERE PLUS DEEP OCEAN



Inferred sink to terrestrial biosphere plus deep ocean over Anthropocene agrees with turnover time based on inventoried emissions minus measured increase in atmospheric stock.

Consistent with constant transfer coefficients over the Anthropocene.

RATE EQUATIONS

$$\frac{dS_a}{dt} = -k_{am}(S_a - S_a^{eq}) + k'_{ma}(S_m - S_m^{eq}) - k_{at}S_a + k_{ta}S_t - F_{tm}^{pi} + Q_{ff}(t) + Q_{lu}(t)$$

$$\frac{dS_m}{dt} = k_{am}(S_a - S_a^{eq}) - k'_{ma}(S_m - S_m^{eq}) - k_{md}S_m + k_{dm}S_d + F_{tm}^{pi} - F_{pc}$$

$$\frac{dS_d}{dt} = k_{md}S_m - k_{dm}S_d + F_{pc}$$

$$\frac{dS_t}{dt} = k_{at}S_a - k_{ta}S_t - Q_{lu}(t)$$

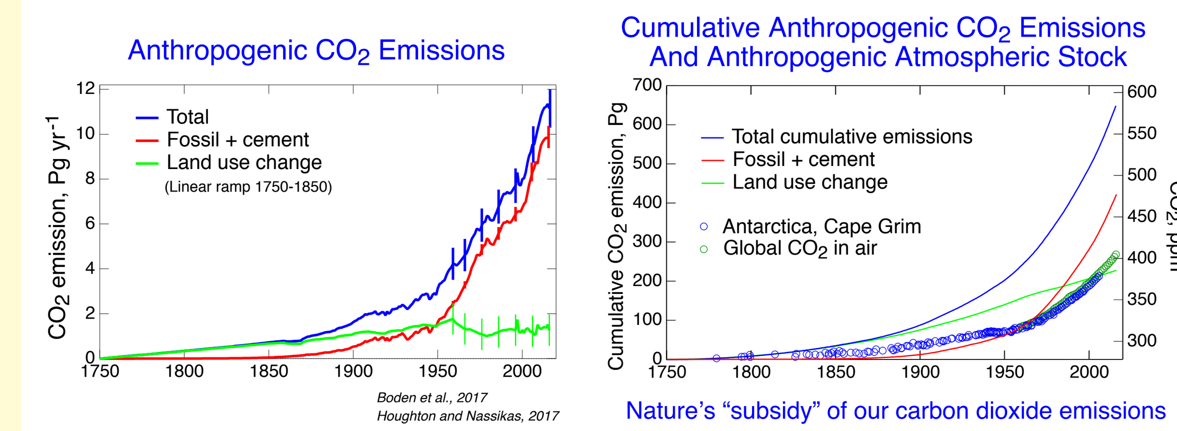
Four coupled ordinary differential equations.

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

Requirements: Transfer coefficients, emissions, initial conditions

EMISSIONS

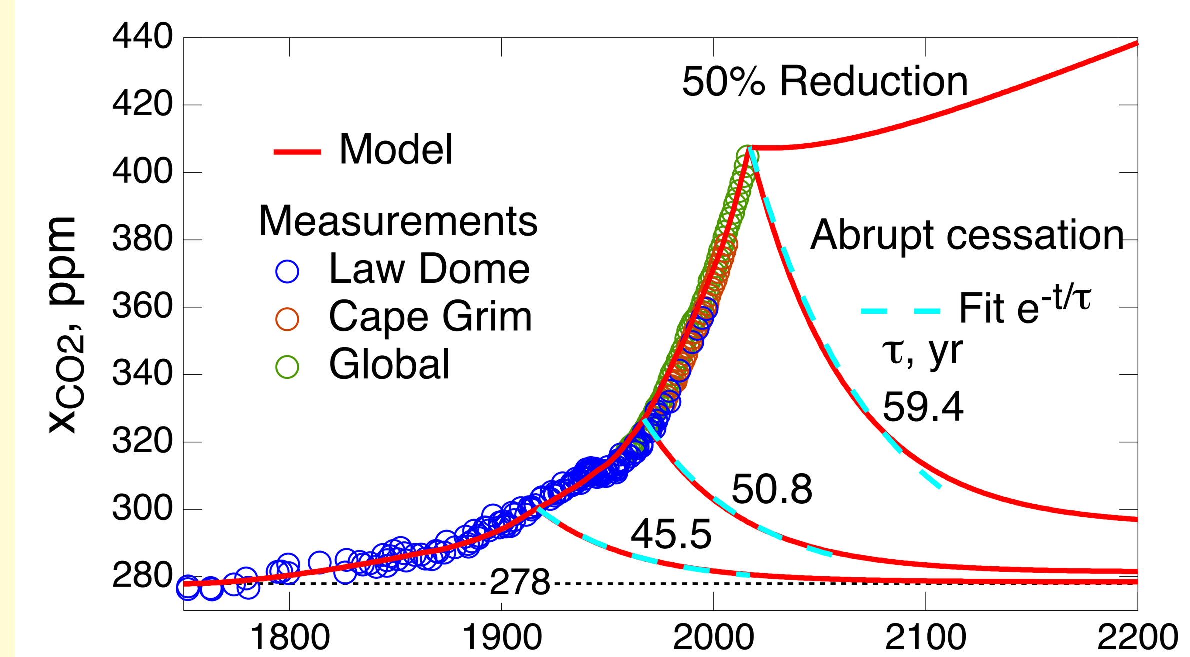
INPUT TO MODEL CALCULATIONS



Nature's "subsidy" of our carbon dioxide emissions

RESULTS

MODEL RESULTS OVER THE ANTHROPOCENE AND FOR EMISSIONS CESSATION OR REDUCTION



Model closely matches observations over Anthropocene.

Cessation experiments show lifetime of excess CO_2 50 – 65 years.

Decreasing anthropogenic emissions by 50% would essentially stabilize excess CO_2, with increase of only 10% over a century.

CONCLUSIONS

The lifetime of atmospheric CO_2 in excess of preindustrial is found to be 50–65 years based both on observations and on a simple model.

This lifetime is several-fold to as much as an order of magnitude shorter than obtained with current carbon-cycle models.

CO_2 is accurately represented over the Anthropocene by a 4-compartment model with three independent, observationally constrained parameters.

Excess atmospheric CO_2 could be stabilized over the next century by decreasing anthropogenic emissions by 50%.