LIFETIME OF EXCESS ATMOSPHERIC CARBON DIOXIDE

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MOTIVATION

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

Reduction in emissions is required to reduce atmospheric CO_2.

Changes in atmospheric CO_2 in response to changes in emissions are ***highly uncertain***.

Abrupt cessation of emissions provides an ***upper limit*** to reduction in atmospheric CO_2 in response to emission changes.

Abrupt cessation of emissions (Zero Emissions Commitment) is widely used as a ***benchmark comparison of CO_2 models***.

LIFETIME DEFINITIONS

Much controversy has arisen because of differing definitions. Here lifetime is ***carefully defined and evaluated***.

Turnover time: Ratio of stock to net exiting flux. Requires careful identification of leaving compartment(s) and sink compartment(s).

Adjustment time (qualitative): The amount of time it would take in the absence of anthropogenic emissions until the CO_2 amount in the air ***recovered substantially*** toward its original value. (Modified from Archer et al., *Ann. Revs.* 2009).

Adjustment time (quantitative): Equivalent 1/*e* lifetime

$$\tau_E = -t / \ln f(t)$$

where $f(t)$ is the fraction of anthropogenic stock remaining at time t after cessation of emissions, generalization of relation between half-life and 1/*e* lifetime. ***Requires model*** (or actual cessation🙂).

Equivalent 1/*e* lifetime is readily evaluated and agrees closely with other measures of adjustment time.

APPROACH

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

Determine turnover times from the budget.

Determine transfer coefficients from the budget.

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

Examine stocks, especially CO_2 mixing ratio, over the Anthropocene thus far and following abrupt cessation of emissions.

Determine adjustment times from CO_2 mixing ratio following cessation of emissions. Compare with turnover times.

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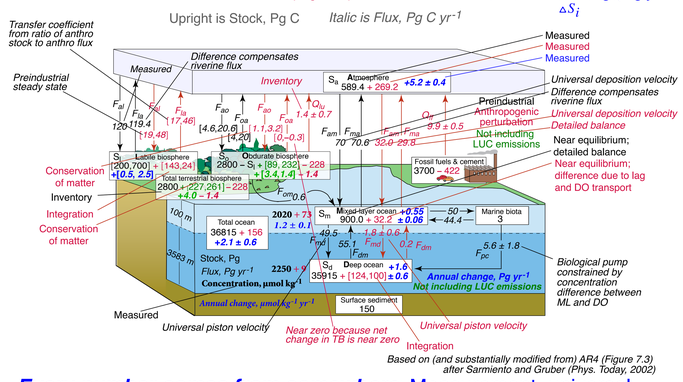
CO_2 BUDGET

Five compartments: **A**tmosphere, **M**L ocean, **D**eep ocean, **L**abile and **O**bdurate biosphere

BLACK is Preindustrial — RED is Anthropogenic perturbation — ***BLUE is Annual change, Pg yr^{-1}*** ΔS_i

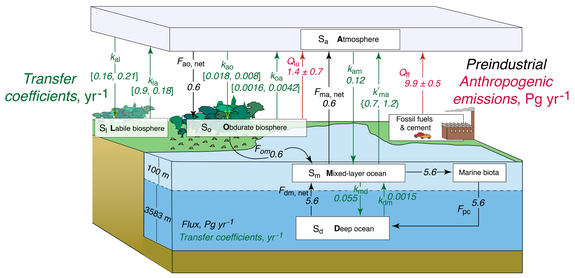
Upright is Stock, Pg C — *Italic is Flux, Pg C yr^{-1}*



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

Apportionment of stocks and fluxes of the two terrestrial biosphere compartments is not fully constrained by observation but is narrowly constrained by ***comparison of model results with observations*** of carbon and radiocarbon, as indicated by square brackets [ ].

TRANSFER COEFFICIENTS



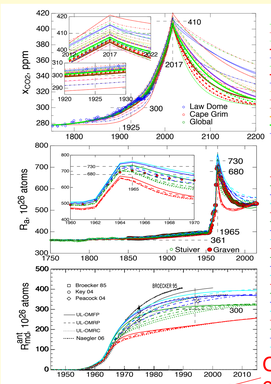
Uncertainties due to uncertain apportionment between terrestrial biosphere compartments are denoted by square brackets [ ].

Because of rapid exchanges between atmosphere and mixed-layer ocean and between atmosphere and labile biosphere (a few years) these compartments are in ***near equilibrium/steady-state***.

In evaluating turnover time of CO_2 to long-lifetime compartments the atmosphere, mixed-layer ocean and labile biosphere must be ***treated as a single compartment***.

CONSTRAINING PARAMETERS

Comparing modeled atmospheric CO_2 and atmospheric and oceanic radiocarbon with observations for different parameter values



Modeled atmospheric CO_2 for historical emissions and after abrupt cessation of emissions in 2017

Modeled radiocarbon for historical emissions.

Model accurately captures increase in radiocarbon due to weapons testing.

Only two adjustable parameters, constrained by observations.

Parameters S_l^{pi} and b denote preindustrial stock in labile biosphere and exponent characterizing increase in gross primary productivity with increasing atmospheric CO_2.

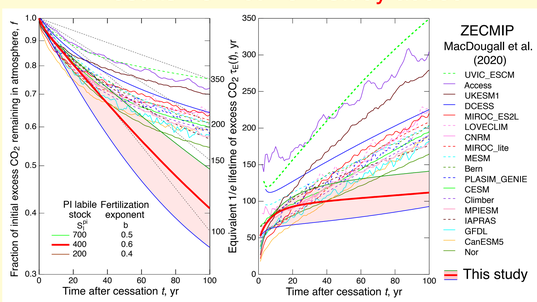
Comparison with observations permits ***exclusion of parameter pairs inconsistent with observations***.

PRESENT & PRIOR RESULTS

Decay and lifetime of excess atmospheric CO_2 after abrupt cessation of emissions

Calculated and redrawn from Zero Emissions Commitment Intercomparison

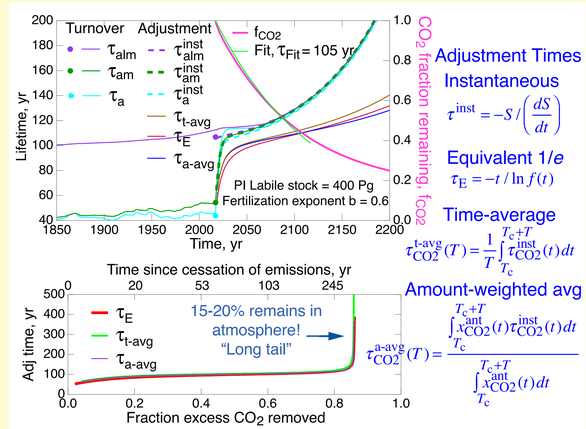
Results from current study added



Current carbon cycle models give lifetime of excess CO_2 over first 100 years ranging from 150 to 350 yr.

Model developed here gives lifetime 110 ± 40 yr.

MULTIPLE MEASURES OF LIFETIME



Adjustment Times

Instantaneous

$$\tau^{inst} = -S \left/ \left(\frac{dS}{dt} \right) \right.$$

Equivalent 1/*e*

$$\tau_E = -t / \ln f(t)$$

Time-average

$$\tau_{CO_2}^{t\text{-avg}}(T) = \frac{1}{T} \int_{T_c}^{T_c+T} \tau_{CO_2}^{inst}(t)\,dt$$

Amount-weighted avg

$$\tau_{CO_2}^{a\text{-avg}}(T) = \frac{\int_{T_c}^{T_c+T} x_{CO_2}^{ant}(t)\,\tau_{CO_2}^{inst}(t)\,dt}{\int_{T_c}^{T_c+T} x_{CO_2}^{ant}(t)\,dt}$$

Turnover times from observations and model for excess carbon, in atmosphere τ_a, atmosphere + ML ocean τ_{am}, and atmosphere + labile terrestrial biosphere + ML ocean τ_{alm}; instantaneous, time-average, and amount- average adjustment times and equivalent 1/*e* lifetime for atmospheric CO_2 τ_E; fractional excess atmospheric CO_2, and decaying exponential fit over initial 100 years after cessation.

Prior to cessation, turnover times τ_a and τ_{am} are ***artificially short*** because of transfer into other short-lived reservoirs; immediately after cesation, all turnover times agree and agree with instantaneous adjustment times. Turnover time τ_{alm} ***changes little at time of cessation, indicative of proper definition***.

Average adjustment times, equivalent 1/*e* lifetime τ_E, and time constant of exponential fit τ_{Fit} agree closely, confirming ***proper identification of multiple measures of lifetime***.

CONCLUSIONS

The lifetime of atmospheric CO_2 in excess of preindustrial is found to be 110 ± 40 years based both on observations and on a simple model.

This lifetime is ***several-fold shorter*** than obtained with current carbon-cycle models.

This lifetime is ***enormously shorter*** than values that include the small long tail; ***don't let the long tail wag the dog!***

CO_2 is accurately represented over the Anthropocene by a 5-compartment model with ***two observationally constrained adjustable parameters***.

Lifetime evaluated by multiple means from observations and models is essentially identical, confirming interpretation.