HOW LONG DOES ANTHROPOGENIC CO$_2$ STAY IN THE ATMOSPHERE?

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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 CO₂!
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

Mauna Loa
- Law Dome
- Cape Grim
- Global

 Etheridge et al., 1996
 Keeling et al., 2001
 Duglokencky & Tans, 2018
CARBON DIOXIDE OVER TIME

Last glacial cycle
- Antarctica

Holocene
- Antarctica

Anthropocene
- Antarctica, Cape Grim
- Antarctica
- Global
- Mauna Loa

Contemporaneous
- Mauna Loa

Mixing ratio, ppm

Time, years before 2010
- 2010
- 1900
- 1800

Year
- 2010
- 1960

Mixing ratio, ppm

Time, years before 1950
- 1950
- 1900
- 1800

Age, kyr
- 600
- 550
- 500

CO₂, ppm

Antarctic composite

Preindustrial

Lüthi (2008)
Etheridge (1996)
Siegenthaler (2005)
MacFarling Meure (2006)
Keeling (1995), updated
Dlugokencky (2018)
ANTHROPOGENIC CARBON DIOXIDE EMISSIONS

CO₂ emission, Pg yr⁻¹

- Total
- Fossil + cement
- Land use change
  (Linear ramp 1750-1850)

Boden et al., 2017
Houghton and Nassikas, 2017
CUMULATIVE ANTHROPOPOGENIC CO$_2$ EMISSIONS

Cumulative CO$_2$ emission, Pg

- **Total**
- **Fossil + cement**
- **Land use change**
CUMULATIVE ANTHROPOGENIC CO$_2$ EMISSIONS AND ANTHROPOGENIC ATMOSPHERIC STOCK

Nature’s “subsidy” of our carbon dioxide emissions
Motivation for this study
The “Cold Turkey” Experiment

Abrupt cessation Of Emissions
Sources of anthropogenic CO₂ → 0

Climate sensitivity
- High
- Best
- Low

ΔT relative to cessation, K

Time after cessation, yr

Climate sensitivity and aerosol forcing magnitude
- High
- Best
- Low

ΔT relative to preindustrial, K

Time after cessation, yr

ΔT relative to preindustrial, K

DECAY OF EXCESS ATMOSPHERIC CO₂ AFTER CESSATION OF EMISSIONS
Calculated and redrawn from recent publications

Current estimates vary by an order of magnitude!
Lifetime

How is it defined?
How is it determined?
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 CO₂ 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 CO₂ concentration in the air recovers substantially toward its original concentration.

**Qualitative**: Requires a *model*

**Turnover time**: Ratio of Stock to Flux out:

\[ \tau_i^{\text{to}} = \frac{S_i}{\sum_j F_{ij}} = \frac{S_i}{Q - \Delta S_i} \]

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

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

\[ \tau_i^{\text{adj}} = \frac{S_i}{-\frac{dS_i}{dt}}, \quad Q^{\text{ant}} = 0 \]

Requires a *numerical model*
Observationally based
Global CO$_2$ budget
And Turnover time
Of Anthropogenic CO$_2$
CO₂ STOCKS, FLUXES

**Steady state**

\[ \tau = \frac{589}{(120 + 70)} \approx 3 \text{ yr} \]

**Measured**

- Atmosphere: 589.4 Pg
- Preindustrial

**Nearly equal**

1. Gross primary productivity: 120 Pg yr⁻¹
2. Gross respiration: 119.4 Pg yr⁻¹

**Do nothing cycle**

\[ \tau = \frac{36000}{55} \approx 600 \text{ yr} \]

**Near equilibrium**

- Tertiary vegetation, soil, and detritus: 2800 Pg

**Disequilibrium**

- Stock, Pg: 36,815
- Flux, Pg yr⁻¹: 2250
- Concentration, µmol kg⁻¹: 2250

**Universal piston velocity**

**Universal deposition velocity**

- Mixed-layer ocean: 900.0 Pg
- Deep ocean: 35,915 Pg

**Detailed balance**

- Fossil fuels & cement: 3700 Pg
- Marine biota: 3 Pg

**Modified (considerably) from AR4 (2007), Fig. 7.3 after Sarmiento & Gruber, Phys. Today (2002)**
CO₂ STOCKS, FLUXES, AND ANNUAL GROWTH

Preindustrial Anthropogenic perturbation

9.9 ± 0.5

900.0 ± 32.2

3700 – 422

Fossil fuels & cement

36,815 + 156

589.4 + 269.2

+5.2 ± 0.4

Terrestrial vegetation, soil, and detritus

2800 – 228 + 224

8700 – 422

Gross primary productivity

120

1.4 ± 0.7

120

0.6

4.0 ± 1.1

4.0 ± 1.1

4.0 ± 1.1

Universal deposition velocity

70 70.6

32.0 29.8

32.0 29.8

Marine biota

3

Universal piston velocity

5.6 ± 1.8

Fpc

Universal deposition velocity

Marine biota

44.4

50

Detailed balance

Inventory

Preindustrial

Modifications (considerably) from AR4 (2007), Fig. 7.3 after Sarmiento & Gruber, Phys. Today (2002)
CO₂ STOCKS, FLUXES, AND ANNUAL GROWTH

Turnover time = Stock / [Emissions – Growth]

\[ \tau = \frac{(269 + 32)}{(9.9 + 1.4) - (5.2 + 0.55)} = 54 \pm 10 \text{ yr} \]

Preindustrial Anthropogenic perturbation

\[ \tau = \frac{S_{\text{am}}}{Q - \Delta S_{\text{am}}} \]

\[ Q_{\text{Lu}} = 1.4 \pm 0.7 \]

\[ Q_{\text{ff}} = 9.9 \pm 0.5 \]

\[ F_t = 119.4 \]

\[ F_{\text{at}} = 120 \]

\[ F_{\text{am}} = 70 \]

\[ F_{\text{ma}} = 70.6 \]

\[ F_{\text{am}} = 32.0 \]

\[ F_{\text{ma}} = 29.8 \]

\[ F_{\text{pc}} = 3 \]

\[ S_{\text{at}} = 2800 - 228 + 224 \]

\[ S_{\text{am}} = 589.4 + 269.2 + 5.2 \pm 0.4 \]

\[ S_{\text{m}} = 900.0 + 32.2 \pm 0.06 \]

\[ S_{\text{d}} = 35,915 + 124 \pm 0.6 \]

\[ \text{Surface sediment} = 150 \]

\[ \text{Total ocean} = 36,815 + 156 + 2.1 \pm 0.6 \]

\[ \text{Stock, Pg} \]

\[ \text{Flux, Pg yr}^{-1} \]

\[ \text{Concentration, µmol kg}^{-1} \]

\[ 2020 + 73 \]

\[ 2250 + 9 \]

\[ 50 \rightarrow 44.4 \]

\[ 5.6 \pm 1.8 \]

\[ 100 \text{ m} \]

3583 m

\[ \text{Annual change, Pg yr}^{-1} \]

\[ \text{Modified (considerably) from AR4 (2007), Fig. 7.3} \]

\[ \text{after Sarmiento & Gruber, Phys. Today (2002)} \]
Model for Anthropogenic CO$_2$
THE DIFFERENTIAL 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 \( S_m \).

**Required:** Transfer coefficients, emissions, initial conditions
**TRANSFER COEFFICIENTS FOR ANTHRO CO₂**

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**Preindustrial steady state**

Three independent, observationally constrained parameters: \( k_{am}, \nu_p, \) and \( k_{at} \)

**Geophysical property**

- \( k_{am} = F_{am}^{pi} / S_a^{pi} \), global mean deposition velocity
- \( k_{ma} = k_{am} K_{am} \), \( K_{am} = (dS_a/dS_m)_{eq} \), a known function of \( S_a \), 5–10 Acid dissociation chemistry
- \( k_{md} z_m = k_{dm} z_d = \nu_p \), global mean piston velocity, 5.5 m yr⁻¹

**Geophysical property: from obs’d global heat uptake rate**

- \( k_{at} = [(Q_{tot} - dS_a / dt - dS_m / dt - dS_d / dt) / S_{a,ant}] \) 2016

**CO₂-specific**

- By difference

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**Anthropogenic emissions, Pg yr⁻¹**

**Transfer coefficients, yr⁻¹**

- Flux, Pg yr⁻¹
  - Mixed-layer ocean
    - 100 m
    - 3583 m
  - Deep ocean
    - 5.6
  - Marine biota
    - 5.6

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**Preindustrial**

**Transfer coefficients, yr⁻¹**

- \( Q_{lu} \)
  - 1.4 ± 0.7
- \( k_{at} \)
  - 0.015
- \( k_{ta} \)
  - 0.0031
- \( F_{ma,net} \)
  - 0.6
- \( k_{am} \)
  - 0.12
- \( K_{ma} k_{am} \)
  - 0.6–1.2
- \( Q_{ff} \)
  - 9.9 ± 0.5

**Geophysical property**

- Acid dissociation chemistry
  - \( K_{am} = (dS_a/dS_m)_{eq} \), a known function of \( S_a \), 5–10

---

**Terrestrial vegetation, soil, and detritus**

- \( F_{at,net} \)
  - 0.6

**Terrestrial vegetation, soil, and detritus**

- \( 0.015 \)
- \( 0.0031 \)
- \( 0.6 \)
- \( 0.12 \)
- \( 0.6–1.2 \)

---

**Fossil fuels & cement**

**Transfer coefficients, yr⁻¹**

- \( F_{tm} \)
  - 5.6
- \( F_{dm,net} \)
  - 5.6

**Fossil fuels & cement**

- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)

---

**Marine biota**

**Transfer coefficients, yr⁻¹**

- \( F_{pc} \)
  - 5.6

**Marine biota**

- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)

---

**Fossil fuels & cement**

**Transfer coefficients, yr⁻¹**

- \( F_{tm} \)
  - 5.6
- \( F_{dm,net} \)
  - 5.6

**Fossil fuels & cement**

- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)
- \( 5.6 \)
FLUXES OF “OBDURATE” CARBON

Preindustrial steady state determines preindustrial flux of “obdurate” carbon from atmosphere to terrestrial biosphere:

\[ F_{at}^{pi} = k_{at} S_{a}^{pi} = 0.0148 \text{ yr}^{-1} \times 589 \text{ Pg} = 8.7 \text{ Pg yr}^{-1} \]

Much less than gross primary productivity, ~120 Pg yr\(^{-1}\).

Much less than net primary productivity (about of GPP).
CO$_2$ STOCKS, FLUXES, AND ANNUAL GROWTH

Preindustrial
Anthropogenic perturbation

<table>
<thead>
<tr>
<th>Stock, Pg</th>
<th>Flux, Pg yr$^{-1}$</th>
<th>Concentration, µmol kg$^{-1}$</th>
<th>Fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>589.4 + 269.2</td>
<td>+5.2 ± 0.4</td>
<td>$F_{at}t_o$</td>
</tr>
<tr>
<td>Surface sediment</td>
<td>150</td>
<td>-0.01 ± 0.44</td>
<td>$F_{ta}$</td>
</tr>
<tr>
<td>Marine biota</td>
<td>3</td>
<td>5.6 ± 1.8</td>
<td>$F_{pc}$</td>
</tr>
<tr>
<td>Total ocean</td>
<td>36,815 + 156</td>
<td>+2.1 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>Mixed-layer ocean</td>
<td>900.0 + 32.2</td>
<td>+0.55 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>Deep ocean</td>
<td>35,915 + 124</td>
<td>+1.6 ± 0.6</td>
<td></td>
</tr>
</tbody>
</table>

Exchange of Obdurate C

Terrestrial vegetation, soil, and detritus
2800 – 228 + 224

Gross primary productivity
1.4 ± 0.7

Fossil fuels & cement
3700 – 422

Modified (considerably) from AR4 (2007), Fig. 7.3 after Sarmiento & Gruber, Phys. Today (2002)
TRANSFER COEFFICIENT FROM TERRESTRIAL BIOSPHERE TO ATMOSPHERE

Return flux (TB to atmosphere) is slightly less than forward flux because of riverine flux to mixed-layer ocean:

\[ F_{ta}^{pi} = F_{at}^{pi} - F_{tm}^{pi} = 8.7 \text{ Pg yr}^{-1} - 0.6 \text{ Pg yr}^{-1} = 8.1 \text{ Pg yr}^{-1} \]

Flux of obdurate carbon determines transfer coefficient:

\[ k_{ta} = \frac{F_{ta}^{pi}}{S_{t}^{pi}} = \frac{8.1 \text{ Pg yr}^{-1}}{2800 \text{ Pg}} = 0.0029 \text{ yr}^{-1} \]

Lifetime of obdurate carbon:

\[ \tau_t = \frac{S_{t}^{pi}}{F_{at}^{pi}} = 321 \text{ yr} \]

Much longer than based on GPP, 23 yr \((\text{Carvalhais et al., 2014})\).
SINK RATE INTO TERRESTRIAL BIOSPHERE PLUS DEEP OCEAN

Assumed sink to terrestrial biosphere plus deep ocean agrees with sink based on measured \textit{and modeled} increase in atmospheric stock and inventoried emissions.
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.
DEcay of excess atmospheric CO₂ after cessation of emissions
Calculated and redrawn from recent publications

Lifetime (50 – 60 yr) is much shorter than given in prior studies.
Model allows examination of stocks in the several compartments. Net TB is TB uptake minus net deforestation. Near zero at present.
Jump in TB is due to cessation of deforestation.

After cessation of emissions Deep ocean and Terrestrial biosphere continue to draw down CO$_2$ at prior rate.
Near equilibrium justifies treating the two compartments as a single compartment to determine lifetime of anthropogenic CO₂. Decrease in difference due to cessation of annual emissions causes jump in atmospheric turnover time.
Comparisons With Observations And Other models
COMPARISON WITH OBSERVATIONS AND OTHER MODELS

Anthropogenic ocean uptake rate

Anthro ocean uptake, Pg yr⁻¹

Observations
- Landschützter
- Rödenbeck
- Wang
- Takahashi
- Gruber
- Graven

Present model

CMIP5 Multimodel mean

GCB17 Multimodel mean
Lifetime of Anthropogenic CO$_2$
By Multiple measures
The lifetime of excess CO$_2$ is shown by multiple measures to be about 50 – 60 years.
When Freeman Dyson met with Fermi in 1953, Fermi welcomed him politely but quickly put aside the graphs he was being shown that indicated agreement between theory and experiment.

When Dyson emphasized the agreement, Fermi asked him how many free parameters he had used to obtain the fit.

“Four,” Dyson replied.

Smiling, Fermi remarked, “I remember my old friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk.”

There was little to add.

_Segrè and Hoerlin, The Pope of Physics (biography of Fermi)_
DEPENDENCE ON TERRESTRIAL BIOSPHERE STOCK

Decrease in atmospheric CO$_2$ is insensitive to value of stock in terrestrial biosphere.
What if?
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 CO₂ is found to be about 50 – 60 years by multiple measures.

This lifetime is much shorter than most present estimates.

Atmospheric CO₂ 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 CO₂ over the Anthropocene and can be used with confidence to assess the consequences of prospective changes in emissions.