Where, Oh, Where has all the Carbon Gone?

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The Papers


Radiocarbon: a Quick Review

• $^{14}\text{C}$ is a radioactive isotope of carbon
• $t_{1/2}=5730$ years
• Produced in the upper atmosphere from nitrogen by cosmic ray produced neutrons:
  $$^{14}\text{N} + \text{n} \Rightarrow ^{14}\text{C} + \text{p}$$
• Production therefore independent of atmospheric $\text{pCO}_2$
• Decays back to nitrogen by beta decay:
  $$^{14}\text{C} \Rightarrow ^{14}\text{N} + \beta$$
Suess Effect, 1953

\[ \Delta^{14}C_{atm} \Rightarrow \frac{^{14}C_{atm}}{^{12}C_{natural} + ^{12}C_{anthro}} \]

Graphs depicting $\Delta^{14}C$ % vs. years removed due to copyright restrictions.
On the Shoulders of Giants

Arrhenius, S., "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground"
*Philosophical Magazine* 41, 237-276 (1896)

“some of the atmospheric gases absorb considerable quantities of heat”

“The selective absorption of the atmosphere…is not exerted by the chief mass of the air, but in a high degree by aqueous vapour and carbonic acid, which are present in the air in small quantities”

Arrhenius calculated in this paper that a doubling of CO\textsubscript{2} would cause a temperature rise of 5 °C. Current IPCC estimates have it between 1.5 and 4.5 °C.
Summary Revelle & Suess, 1957

- Pre-Keeling Curve of atmospheric CO$_2$
- Assumed Ocean-Atmosphere CO$_2$ reservoirs as a closed system (no land sink)
- Determined a $\tau_{atm}$ for CO$_2$ of $\sim$10 years based on $^{14}$C age of marine materials and the effects of anthropogenic CO$_2$ on atmospheric $^{14}$C
- The “Revelle Factor”
  \[ \gamma = \frac{r}{s} \frac{S_0}{A_0} \]
  \[ R = \frac{\partial p_{CO_2}}{p_{CO_2}} \cdot \frac{DIC}{\partial DIC} \]
Effect of $\gamma$ (Revelle Factor) on Atmospheric $\text{CO}_2$

Revelle & Suess, 1957

Figure depicting expected secular increase in the $\text{CO}_2$ concentration of air removed due to copyright restrictions.
Paraphrase: Using radiocarbon measurements to calculate diffusive and advective fluxes. These fluxes can be used to put real-time into dynamic circulation models of the ocean.

The Toolbox: Solving the general equation for radioactive nonconservative tracers in the 1-D diffusion-advection model:

Formula removed due to copyright restrictions.

by successively fitting concentration profiles with related tracer classes.
Stable Conservative (SC) Tracers  Craig, 1969

• Salinity and Temperature
• Have the most simplistic dynamics, $J = \lambda = 0$
• Can be used to compute $z^* = K/\omega \approx 1\text{km}$, the 1-D mixing parameter
• Constraints on $K$ give $0.3 < \omega < 30 \text{ m/yr}$

Formula removed due to copyright restrictions.

A BIG MESS  EASY!

Formula removed due to copyright restrictions.
Stable Nonconservative Tracers  
Craig, 1969

- Total CO$_2$ and dissolved O$_2$
- $\lambda = 0$, $J \neq 0$
- Now we can calculate $J/\omega = 0.8$ from stable carbon profiles
- Remineralization constraints lead to a rough estimate of $\omega = 6 \pm 3$ m/yr
- $\tau^{\text{DIC}}_{\text{part.flux}} = 10 \times \tau^{\text{DIC}}_{\text{mix}}$

Graph depicting $\Sigma$CO$_2$ profiles in the Pacific at 31°S [Weiss and Craig, 1968] and 0°-30N [Li et al., 1969] removed due to copyright restrictions.
• $\lambda \neq 0, J \neq 0$: Use the full diffusion-advection model with previously fixed parameters from the stable tracers

• In the abyss, $^{14}\text{C}$ decay rate balanced by particle input: $J^* \approx \lambda C^*$

• RNC profiles are fit with a value of $\lambda/\omega$ and from this, Craig infers $\omega = 6.8$ m/yr
Conclusions

• Diffusion-advection calculations from $\sum$CO$_2$, dissolved O$_2$, and $^{14}$C give estimates of
  – $\omega = 7$ m/yr
  – $K = 2$ cm$^2$/sec

• Horizontal flow velocities could not be calculated because $J^* \approx \lambda C^*$, thus it cannot be considered a “closed system” to compute a record of elapsed time

• Analytical precision of $^{14}$C needs improvement or $^{14}$C half life is slightly too long for better resolution of $\omega$

• He$^4$ & He$^3$???
Methods Stuiver, Quay, & Ostlund, 1983

- 2200 $^{14}$C samples taken from Atlantic, Pacific and Indian Oceans
- $^{14}$C mass balances done on basin-wide box models, allowing for heterogeneity in $^{14}$C
- $^{14}$C nearly constant in Antarctic circumpolar waters, providing a great boundary condition
- Transport rates determined based on mass and $^{14}$C balances for Indian and Pacific
- NADW mass transport set at 14 Sv from tracer and geostrophic calculations

Box model of the deep ocean removed due to copyright restrictions.
Findings  Stuiver, Quay, & Ostlund, 1983

• General decrease in $\Delta^{14}C$ from Atlantic to Antarctic and from Antarctic to Indian and Pacific

Graphs depicting average $\Delta^{14}C$ values of waters below a depth of 1500m for Atlantic, Pacific, and Indian ocean GEOSECS stations removed due to copyright restrictions.
Conclusions

• Water replacement times:
  – Atlantic: 275 years
  – Indian: 250 years
  – Pacific: 510 years
  – Deep Circumpolar Water: 85 years
  – Mean World Oceans: 500 years

• Pacific mean upwelling rate of 5 m/yr (consistent with Craig, 1969)
Partitioning Carbon Fluxes and Reservoirs

Siegenthaler & Sarmiento, 1993

Figures of Pre-industrial carbon cycle and carbon cycle (1980-89) removed due to copyright restrictions.

Table of budget of annual anthropogenic CO$_2$ perturbations removed due to copyright restrictions.
Interhemispheric Concentration Difference and CO$_2$ sinks

Siegenthaler & Sarmiento, 1993

- 95% of fossil fuel emissions occur in NH
- SH atm. CO$_2$ increase lags behind NH
- NH sinks exceed those in the SH

Siegenthaler & Sarmiento, 1993

- Graph of CO$_2$ concentration vs. year (1955-95) removed due to copyright restrictions.
- Graph of CO$_2$ difference NH-SH vs. fossil-fuel emission removed due to copyright restrictions.
- Figure of column inventory of anthropogenic CO$_2$ in the ocean removed due to copyright restrictions.

Sabine, et al, 2004
Conclusions

Siegenthaler & Sarmiento, 1993

• Ocean has taken up about 1/3 of anthropogenic CO₂
• Direct Air-Sea flux measurements of CO₂ provide only limited information on oceanic uptake of anthropogenic CO₂
• Rate limiting step for oceanic CO₂ uptake is the vertical water transport
• Missing sink/imbalance likely due to soils and vegetations have accumulated carbon due to anthropogenic CO₂ or nitrogen fertilization