Where, Oh, Where has all the Carbon Gone?

Anonymous Student

3/9/06

The Papers

Revelle, R. and Suess, H., 1957: Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 during the Past Decades, *Tellus IX*, 1, p.18-27.

Craig, H., 1969: Abyssal Carbon and Radiocarbon in the Pacific, *Journal of Geophysical Research*,Vol. 74, No. 23, pp. 5491-5506

Stuiver, M., Quay, P., Ostlund, H., 1983. Abyssal Water Carbon-14 Distribution and the Age of the World Oceans, *Science*, Vol. 219, pp. 849-851.

Siegenthaler, U., Sarmiento, J., 1993, Atmospheric carbon dioxide and the ocean, *Nature*, Vol. 365, pp 119-125.

Radiocarbon: a Quick Review

- ^{14}C is a radioactive isotope of carbon
- $t_{1/2}$=5730 years
- Produced in the upper atmosphere from nitrogen by cosmic ray produced neutrons:

$$^{14}N + n \Rightarrow {}^{14}C + p$$

- Production therefore independent of atmospheric pCO_2
- Decays back to nitrogen by beta decay:

$$^{14}C \Rightarrow {}^{14}N + \beta$$

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_2 would cause a temperature rise of 5 °C. Current IPCC estimates have it between 1.5 and 4.5 °C.

#1

Revelle, R. and Suess, H., 1957: Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 during the Past Decades, *Tellus IX*, 1, p.18-27.

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 τ_{atm} for CO_2 of ~10 years based on ^{14}C age of marine materials and the effects of anthropogenic CO_2 on atmospheric ^{14}C
- The "Revelle Factor"

$$\gamma = r/s * S_0/A_0 \qquad \Leftrightarrow$$

$$R = \partial pCO_2/pCO_2 * DIC/\partial DIC$$

Effect of γ (Revelle Factor) on Atmospheric CO_2

Revelle & Suess, 1957

Figure depicting expected secular increase in the CO_2 concentration of air removed due to copyright restrictions.

Année Géophysique Internationale symbol removed due to copyright restrictions.

#2

Craig, H., 1969: Abyssal Carbon and Radiocarbon in the Pacific, *Journal of Geophysical Research*,Vol. 74, No. 23, pp. 5491-5506

Abyssal Carbon and Radiocarbon in the Pacific

Craig, 1969

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
  $0.3 < \omega < 30$ m/yr

Graph depicting schematic salinity profiles in the vertical diffusion-advection model removed due to copyright restrictions.

A BIG MESS

EASY!

Formula removed due to copyright restrictions.

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

$$\omega = 6 \pm 3 \text{ m/yr}$$

- $\tau^{DIC}_{part.flux} = 10 * \tau^{DIC}_{mix}$

Graph depicting ΣCO_2 profiles in the Pacific at 31^{O}S [Weiss and Craig, 1968] and 0^{0}-30N [Li et al., 1969] removed due to copyright restrictions.

Radioactive Tracers

Craig, 1969

- $\lambda \neq 0$, $J \neq 0$: Use the full diffusion-advection model with previously fixed parameters from the stable tracers
- In the abyss, C^{14} decay rate balanced by particle input: $J^* \approx \lambda C^*$
- RNC profiles are fit with a value of λ/ω and from this, Craig infers a $\omega = 6.8$ m/yr

Conclusions

Craig, 1969

- 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 ω
- He^4 & He^3???

#3

Stuiver, M., Quay, P., Ostlund, H., 1983. Abyssal Water Carbon-14 Distribution and the Age of the World Oceans, *Science*, Vol. 219, pp. 849-851.

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

Stuiver, Quay, & Ostlund, 1983

- 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)

#4

Siegenthaler, U., Sarmiento, J., 1993, Atmospheric carbon dioxide and the ocean, *Nature*, Vol. 365, pp 119-125.

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

Graph of CO_2 concentration vs. year (1955-95) removed due to copyright restrictions.

Siegenthaler & Sarmiento, 1993

Graph of CO_2 difference NH-SH vs. fossil-fuel emission removed due to copyright restrictions.

- 95% of fossil fuel emissions occur in NH
- SH atm. CO_2 increase lags behind NH
- NH sinks exceed those in the SH

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 CO_2
- Direct Air-Sea flux measurements of CO_2 provide only limited information on oceanic uptake of anthropogenic CO_2
- Rate limiting step for oceanic CO_2 uptake is the vertical water transport
- Missing sink/ imbalance likely due to soils and vegetations have accumulated carbon due to anthropogenic CO_2 or nitrogen fertilization