Atmospheric signatures of changing global biogeochemistry

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Or “How I learned to stop worrying and love the biosphere”

In collaboration with
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Controls on atmospheric CO$_2$ increase

\[ \text{CO}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \leftrightarrow 2 \text{HCO}_3^- \]
### CO$_2$ budget 2000-2010 (Pg C/yr)

<table>
<thead>
<tr>
<th>Source Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel emissions</td>
<td>7.8 ± 0.6</td>
</tr>
<tr>
<td>Land use emissions</td>
<td>1.1 ± 0.8</td>
</tr>
<tr>
<td>Total Sources</td>
<td>8.9 ± 1.0</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>4.0 ± 0.2</td>
</tr>
<tr>
<td>Ocean sink</td>
<td>2.3 ± 0.7</td>
</tr>
<tr>
<td>Residual land sink</td>
<td>2.6 ± 1.2</td>
</tr>
<tr>
<td>Total Sinks</td>
<td>8.9 ± 1.0</td>
</tr>
</tbody>
</table>

- IPCC AR5
Historic Carbon Sources and Sinks

IPCC Ar5, Figure 6.8
Controls on atmospheric CO$_2$ and O$_2$

Land
Plants

Industry

Oceans

CO$_2$ + CO$_3^{2-}$ + H$_2$O $\leftrightarrow$ 2 HCO$_3^-$
Measurements of CO₂ Concentration and isotopes: $^{13}\text{C}/^{12}\text{C}$, $^{18}\text{O}/^{16}\text{O}$, $^{14}\text{C}$
Measurements of O₂/N₂ ratio and Ar/N₂ ratio
Archive of pure CO₂ extracted from samples
Scripps O$_2$ Program

**Scripps O$_2$ Program Elements**
- Flask network, 10 stations
- Continuous measurements at La Jolla
- Measure CO$_2$, O$_2$/N$_2$ ratio and Ar/N$_2$ ratio
- Methods development
- Calibration facility

Project Website: ScrippsO2.ucsd.edu
\[ \delta(O_2/N_2) = \frac{(O_2 / N_2)_{sample} - (O_2 / N_2)_{reference}}{(O_2 / N_2)_{reference}} \]

4.8 per meg ~ 1 ppm
Vector diagram of O$_2$ and CO$_2$ changes

Budget for 1991 to 2001
Ocean uptake = 2.45 ±0.58 Pg C yr$^{-1}$
Land uptake = 1.05 ± 0.80 Pg C yr$^{-1}$
CO$_2$ concentration at selected stations

Cycle at Barrow driven mostly by boreal and temperate forests

Amplitude increase over 50 years ~ 50% or 0.8% /yr
Arctic landscapes

- Tundra (north slope)
- Boreal forest
Figure 7. Reconstruction of Eocene High Arctic rain forest environment with hippo-like Coryphodon in the foreground; inset shows detail of Eocene Arctic tapir Thulidonta. Both images are courtesy of the American Museum of Natural History (© AMNH/D. Finnin).
What role does ocean biogeochemistry play in CO$_2$ uptake, beyond a passive response to rising CO$_2$?

-> Conventional wisdom is a rather small role.
Future projections show only small range in ocean responses
“Observations” support much smaller ocean than land variability in recent past

Ocean interannual variability = $\sim\pm 0.2$ Pg C yr$^{-1}$

Ocean models typically also yield $\sim\pm 0.2$ Pg C yr$^{-1}$* 

IPCC AR5, Figure 6.9

*Wanninkhof et al, 2013, Biogeosciences
But... Ocean biogeochemical response to climate changes may be underestimated.

(1) Glacial-interglacial CO₂ “puzzle”.

(2) Magnitude of interannual variability might be larger than estimated by models and “observation”

   Roedenbeck et al. (2013, BGD) ~ ±0.31 Pg C yr⁻¹

(3) Ocean models underestimate variability in “atmospheric potential oxygen”

(4) Largest perturbation to CO₂ growth rate in 1940s might have been (mostly) oceanic.
Also... improved ocean fluxes needed for inverse calculations of land fluxes

Repeat hydrography and surface ocean pCO2 measurements won’t fully address need on decadal time scale.

Measurements of atmospheric O2 may help fill this gap.
Atmospheric $\text{CO}_2$ & $\text{O}_2$ coupling

Ocean $\text{CO}_2$ uptake:

$$\text{H}_2\text{O} + \text{CO}_2 + \text{CO}_3^- \leftrightarrow 2\text{HCO}_3^-$$
Atmospheric potential oxygen

Ocean CO₂ uptake:

\[ \text{H}_2\text{O} + \text{CO}_2 + \text{CO}_3^- \leftrightarrow 2\text{HCO}_3^- \]
What about changes in functioning of ocean biota?

\[ \delta(O_2/N_2) = \frac{(O_2 / N_2)_{sample} - (O_2 / N_2)_{reference}}{(O_2 / N_2)_{reference}} \]

4.8 per meg ~ 1 ppm
APO: a tracer of oceanic exchanges
Long-term trend in APO

Trend accounts for fossil-fuel and ocean response to rising CO₂
Seasonal APO cycles as model test

Palmer Station (65°S)

Nevsion et al., in prep, 2013
Seasonal cycles as metric of long-term changes
Programmatic Needs:

(1) Sustain $O_2$ observations as part of carbon observing system

(2) Incorporate $O_2$ constraints into CarbonTracker and other assimilation systems.

Ongoing Collaboration to take first steps by using APO to improve Carbon Tracker “priors”
Laure Resplendy, Ralph Keeling SIO
Andy Jacobsen, NOAA-GMD
Samar Khatiwala, Oxford
Christian Roedenbeck, Martin Heimann (MPI, Jena)
APO gradient with latitude*

See poster by Laure Resplandy
Thank You
Future CO$_2$ fluxes

- Fossil-fuel emissions
- Net land biosphere

Business as Usual
Stabilization at 450 ppm
Major World Carbon Pools

- Atmosphere: 800 billions of tons of C
- Oceans: ~40000 billions of tons of C
- Fossil-fuel resource base: 4300 billions of tons of C
- Permafrost: 1400 billions of tons of C
- Peat: 450 billions of tons of C
- Plants: 650 billions of tons of C
- Others/Soils: 2000 billions of tons of C

Units: billions of tons of C
Land

Ocean

**Atmospheric Circulation**

**Ocean Circulation**

Air

$F_{O_2} = K([O_2] - [O_2]_{eq})$

$F_{CO_2} = K([CO_2] - [CO_2]_{eq})$

**Processes driving air-sea fluxes**

1. Changes in atmosphere
2. Changes within the ocean
   a) Warming/cooling
   b) Photosynth/Resp.
   c) CaCO$_3$ precip/diss

**Photosynthesis:** $CO_2 \rightarrow C_{org} + 1.3*O_2$

**Respiration:** $1.3*O_2 + C_{org} \rightarrow CO_2$

**Linking air-sea O$_2$ and CO$_2$ fluxes** 1. Mechanistic Framework