Carbon in water: Open ocean, coastal zone and inland waters

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JASON: Carbon Treaty Verification

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How does water impact carbon management and carbon treaty verification?

• Open ocean = ultimate long term sink
  – Monitoring to know if policy sufficient for long term goals

• Coastal zone = land/ocean link
  – Large, variable fluxes in close proximity to cities and boundaries in inversions – constraints needed
  – Export of carbon from the land to the coastal zone = an accounting problem

• Inland waters
  – Significant CO$_2$ and CH$_4$ fluxes, anthropogenic controls
  – Captured in top-down inversions, but not bottom-up
Open Ocean = Ultimate Sink

Mean = Known
Variability = Small (with regional/global average)
Trend = Unknown
Total ocean anthropogenic CO$_2$ uptake (1800-1994)

Ocean has taken up 48% of all fossil fuel carbon

Sabine et al. 2004
Climatological air-sea CO$_2$ flux

- Dominant flux control is surface ocean pCO$_2$

Takahashi et al. 2009
$p\text{CO}_2^{\text{ocean}}$ is determined by

- Solubility effects
- Biological effects
Solubility effect of temperature

Cooling waters absorb CO$_2$
Warming waters release CO$_2$

WARM

COLD
Impact of Atmospheric pCO₂
Biological effect
Biological effect

Sunlight

DIC

Nutrients

Phytoplankton

Zooplankton

Detritus

CO₂

Export

DIC

Nutrients

Summer ML

Max ML
Seasonal cycle due to convection and biology
Upwelling drives return of cold and carbon-enriched deep waters to surface

(1) Cooling of northward flowing waters
(2) High biological productivity
Climatological comparisons
2000: $2.0 \pm 1.0$ PgC/yr

Takahashi et al. 2009
Compare to ocean inversion

Gruber et al. 2009
Climatological flux 1990’s-early 2000’s

<table>
<thead>
<tr>
<th>Paper (method)</th>
<th>PgC/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gruber et al. 2009 (ocean inversion)</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>Takahashi et al. 2009 (in situ pCO$_2$)</td>
<td>2.0 ± 1.0</td>
</tr>
</tbody>
</table>

Variety of methods now agree within uncertainty

Other estimates also agree (see Gruber et al. 2009)
Variability in the air-sea CO$_2$ flux

Sarmiento and Gruber 2002
Interannual variability dominated by ENSO cycle

McKinley et al. 2004a
Forward models and inversion of Rodenbeck et al. (2003) agree

±0.3 PgC/y (1σ)

McKinley et al. 2004b
Increasing atmospheric fraction of anthropogenic CO₂? Oceans role?

“The hypothesis of a recent or secular trend in the AF cannot be supported on the basis of the available data and its accuracy.” Knorr 2009

Canadell et al. 2007

LeQuéré et al. 2009
North Atlantic Trends?
VOS datasets, linear pCO$_2$ trend 1990-2006 (Schuster et al. 2009)

pCO$_2^{ocean}$ Trend
($\mu$atm/yr)

If pCO$_2^{ocean}$ trend $>$ pCO$_2^{atm}$ trend, sink is declinding

Data of
Corbiere et al. 2007
Shuster & Watson 2007
Bates 2007
Olsen et al. 2004
Santana-Casiano et al. 2007

ATM = 1.8
VOS data coverage poor

2005 – A good year

Watson et al. 2009

Corbiere et al. 2007

Iceland to Newfoundland
Observed 1990-2006

Modeled, 1992-2006

$pCO_2^{\text{ocean}}$ (µatm/yr)

Schuster et al. 2009

Generally consistent <45N, but inconsistent >45N

Ullman et al. 2009
### W. Subpolar Gyre

#### SURATLANT

<table>
<thead>
<tr>
<th>Study</th>
<th>Years</th>
<th>Trend (µatm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DATA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corbière et al. 07</td>
<td>93-03</td>
<td>2.8</td>
</tr>
<tr>
<td>Schuster et al. 09</td>
<td>93-05</td>
<td>4.0 ± 0.48</td>
</tr>
<tr>
<td><strong>MODELS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thomas et al. 08</td>
<td>95-04</td>
<td>3.0</td>
</tr>
<tr>
<td>Ullman et al. 09</td>
<td>92-06</td>
<td>0.9 ± 0.02</td>
</tr>
<tr>
<td>Rodenbeck et al. 05</td>
<td>93-05</td>
<td>~1 (all subpolar)</td>
</tr>
</tbody>
</table>
Are observed trend estimates robust to analysis methodology?
Region labels
pCO$_2$ Analysis
Schuster et al. (2009)
pCO$_2$ Analysis
Schuster et al. (2009)
Reanalysis of data (1) Update SSS-ALK, (2) Averaging strategy; Confirmed with sampled vs. full model
Data-based trend now indistinguishable from atmospheric trend

ATM = 1.8
Apply methodology to recently-released Takahashi database in biogeographic regions

McKinley and Fay, in prep.
Coastal = Large & variable, in close proximity

Mean = Known in only a few regions
Variability = Large
Trend = Unknown
Coastal CO$_2$ Flux Estimates in The First State of Carbon Cycle Report

Air-Sea CO$_2$ Flux (g C m$^{-2}$ per year)

Net efflux in North American coastal oceans: $+1.6 \pm 35.6$ Tg C y$^{-1}$

Chavez et al. (2007)
Highly variable

Jul-Sep 2005

Monterey Bay

Temp | Salinity | pCO$_2$

380 ppm

El Nino

SOCRR Fig 15.5
Do these large, variable coastal fluxes impact regional carbon budgeting?

*CarbonTracker* 1°x1° land fluxes

2001–2008 mean

North American Carbon Program
www.nacarbon.org
Modeled CO$_2$ flux

University of Wisconsin - Madison
Val Bennington - Prof. Galen McKinley

CO$_2$ Flux - color shaded - mol/m$^2$/yr
SST - black contours overlay - °C

1997-01-02 00:00:00Z

McKinley et al. *in prep*
What is the influence of this CO$_2$ flux on the WLEF tower in Park Falls, WI?
Lake influence on WLEF tower

72-hour particle backtrajectory analysis for 2004 (WRF model with STILT – A. Michalak, Michigan)
In winter and spring, Lake flux is significant to observed $pCO_2^{\text{air}}$ changes. Vasys et al. *in prep*
Coastal CO₂ observational network

...more and more underway pCO₂ systems on research vessels and volunteer ships (VOS)
UPWELLING SYSTEMS (N. American West Coast)

- Dense (cold) water at coast
- Filaments transport dense water offshore -- CROSS-SHELF transport
- Freshwater runoff effects do not persist
- Is the surface export of POC by phytoplankton balanced by DIC upwelling?
<table>
<thead>
<tr>
<th>Method</th>
<th>Latitude N</th>
<th>Annual flux (Tg C)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatology</td>
<td>~8–55°</td>
<td>– 13 ± 26</td>
<td>Chavez et al. (2007)</td>
</tr>
<tr>
<td>SOM (U.S. West Coast–Baja)</td>
<td>22–50°</td>
<td>– 17</td>
<td>Hales et al. (2007)</td>
</tr>
<tr>
<td>SOM (Mexico–Panama)</td>
<td>5–25°</td>
<td>-0.5</td>
<td>Hales et al. (2008)</td>
</tr>
<tr>
<td>ROMS (U.S. West Coast)</td>
<td>24–48°</td>
<td>weak net source</td>
<td>Plattner et al. (2008)</td>
</tr>
<tr>
<td>SOM (U.S.–Central America)</td>
<td>5–50°</td>
<td>– 30</td>
<td>Alin et al. (2009)</td>
</tr>
</tbody>
</table>
Satellite-based Synthesis of CO₂ Observations

Remote sensing climatologies

\[ \text{Flux} = k \, s \, \Delta f CO₂ \]

\[ k = f (U_{10}, \text{SST}) \]

CO₂ flux

Wind speed

\[ pCO₂ = f (\text{Alk}, TCO₂, T, S) \]

\[ TCO₂ = TCO₂0 + \frac{\partial TCO₂}{\partial T} \Delta T \text{mix} + \frac{\partial TCO₂}{\partial \text{Chl}} \Delta \text{Chl}_{\text{bio}} \]

\[ \text{Alk} = \text{Alk}_0 - 0.15 \Delta TCO₂ \]

Hales et al., in prep

Field CO₂ data

SOM defines regions

Non-linear model

RS data
Inland waters = damp the terrestrial sink

Mean  = Poorly known
Variability = Large
Trend  = Unknown, but expected significant
Inland waters are significant to the global carbon cycle

CO₂ evasion

PgC/yr

Land 1.9
2.9

Inland waters

0.75 1.4 (40-50%)

Ocean

0.9 (30-50%)

Sediment storage

0.23 0.6 (10-20%)

Cole et al. (2007), Tranvik et al. (2009)
Projected changes

- Regional changes in lake distribution
- Increased number of impoundments – esp. tropical hydroelectric
- Increased carbon burial
- Increased $\text{CH}_4$, $\text{CO}_2$ emissions
Accounting for inland waters

- In bottom-up estimates, terrestrial carbon uptake will be overestimated

- In continental scale atmospheric inversions, inland fluxes should be captured
  - But, export and processing in the coastal zone unlikely captured
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Extra Slides
Ocean Carbon and Biogeochemistry

- OCB Overarching Scientific Themes --- Improve understanding and prediction of:
  - oceanic uptake and release of atmospheric CO2 and other greenhouse gases
  - climate-sensitivities of biogeochemical cycles and interactions with ecosystem structure

- OCB Currently Identified Priorities
  - Ocean acidification
  - Terrestrial/coastal carbon fluxes and exchanges
  - Climate sensitivities of and change in ecosystem structure and associated impacts on biogeochemical cycles
  - Mesopelagic and Benthic-pelagic ecological and biogeochemical interactions
  - Ocean carbon uptake and storage

http://www.us-ocb.org/
1995: $2.0 \pm 1.2 \text{ PgC/yr}$

*Takahashi et al. 2002*
Data Density

Red = new