Uptake and Storage of Anthropogenic Carbon

by

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OUTLINE

1. Briefly review how observations contribute to Carbon uptake estimates
2. Describe how we determine ocean carbon inventories
3. Consider issues for understanding future ocean carbon uptake and storage
4. Suggest an approach for where we go from here
Carbon Inventories of Reservoirs that Naturally Exchange Carbon on Time Scales of Decades to Centuries

- Ocean Anth. C = 0.35%
- Soil = 2300 PgC
- Plants = 650 PgC
- Atm. = 775 PgC
- Preind. Atm. C = 76%
- Anth. C = 24%

- Oceans contain ~90% of carbon in this 4 component system
- Anthropogenic component is difficult to detect
Global Carbon Budget for 2000-2005

- Fossil Fuel & Cement Emissions
- Land-Use Land Change sink
- Volcanism

- Fossil Organic Carbon [>6000 -304]
- Rock Carbonates
- Geological Reservoirs

- Air-sea Flux [38,000 +136]
- Ocean [70,500]

- Atmospheric [590 + 185]

- NPP & Fires
- Weathering
- River outgassing
- River export
- Respiration

adapted from Sabine et al., 2004
Based on ~3 million measurements since 1970 and NCEP/DOE/AMIP II reanalysis. Global flux is $1.4 \pm 0.7$ Pg C/yr

Takahashi et al., Deep Sea Res. II, 2009
Surface $CO_2$ observation network
Global Surface CO$_2$ observations by year

The number of annual measurements has been increasing exponentially since for the last 50 years.

A focus on studying ocean carbon in the 1990s led to the instrumenting of many more research ships.

The dramatic increases in the 2000s can be attributed to the instrumenting of commercial ships.

Based on SOCAT version 1 Jan. 2010  From Sabine et al., 2010
New Technologies can Help Expand the Surface $CO_2$ Observation Network

One Example: Integrated MapCO$_2$/Wave Glider system under development
Producing Seasonal CO\textsubscript{2} Flux Maps

- **In situ sampling**: pCO\textsubscript{2}, SST, SSS
- **Remote sensing**: SST, color & wind
  - Soon SSS

**Algorithm development**

\[ p\text{CO}_2 = f(\text{SST}, \text{color}) \]

**Co-located satellite data**

**Apply algorithm to regional SST & color fields to obtain seasonal pCO\textsubscript{2} maps**

**Regional satellite SST & color data**

**Wind data**

**Algorithm development**

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

**Flux = k \Delta p\text{CO}_2**

**Flux maps**
Global Flux Map suggests an interannual variability of 0.23 Pg C

Surface observations have large variability over a wide range of time and space scales making it very difficult to properly isolate the anthropogenic increases. Uptake of 2 Pg C yr\(^{-1}\) only requires a \(\Delta pCO_2\) of 8 ppm.
Several Independent Approaches are Converging on an Estimate of the Anthropogenic CO₂ Uptake

Table 1. Summary of Recent Estimates of the Oceanic Uptake Rate of Anthropogenic CO₂ for the Period of the 1990s and Early 2000s

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimate (Pg C a⁻¹)</th>
<th>Time Period</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimates Based on Oceanic Observations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean Inversion (10 models)</td>
<td>–2.2 ± 0.3</td>
<td>Nominal 1995</td>
<td>this study and Mikaloff - Fletcher et al. [2006]</td>
</tr>
<tr>
<td>Ocean Inversion (3 models)</td>
<td>–1.8 ± 0.4</td>
<td>Nominal 1990</td>
<td>Gloor et al. [2003]</td>
</tr>
<tr>
<td>Air-sea pCO₂ difference (adjusted)</td>
<td>–1.9 ± 0.7</td>
<td>Nominal 2000</td>
<td>Takahashi et al. [2008]</td>
</tr>
<tr>
<td>Air-sea pCO₂ difference (adjusted)</td>
<td>–2.0 ± 60%</td>
<td>Nominal 1995</td>
<td>Takahashi et al. [2002]</td>
</tr>
<tr>
<td>Estimates Based on Atmospheric Observations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric O₂/N₂ ratio</td>
<td>–1.9 ± 0.6</td>
<td>1990–1999</td>
<td>Manning and Keeling [2006]</td>
</tr>
<tr>
<td>Atmospheric O₂/N₂ ratio</td>
<td>–2.2 ± 0.6</td>
<td>1993–2003</td>
<td>Manning and Keeling [2006]</td>
</tr>
<tr>
<td>Atmospheric O₂/N₂ ratio</td>
<td>–1.7 ± 0.5</td>
<td>1993–2002</td>
<td>Bender et al. [2005]</td>
</tr>
<tr>
<td>Atmospheric CO₂ inversions (adjusted)</td>
<td>–1.8 ± 1.0</td>
<td>1992–1996</td>
<td>Gurney et al. [2004]</td>
</tr>
<tr>
<td>Estimates Based on Oceanic and Atmospheric Observations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-sea ¹³C disequilibrium</td>
<td>–1.5 ± 0.9</td>
<td>1985–1995</td>
<td>Gruber and Keeling [2001]</td>
</tr>
<tr>
<td>Deconvolution of atm. ¹³C and CO₂</td>
<td>–2.0 ± 0.8</td>
<td>1985–1995</td>
<td>Joos et al. [1999a]</td>
</tr>
<tr>
<td>Joint atmosphere-ocean inversion</td>
<td>–2.1 ± 0.2</td>
<td>1992–1996</td>
<td>Jacobson et al. [2007b]</td>
</tr>
<tr>
<td>Estimates Based on Ocean Biogeochemistry Models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCMIP-2 (13 models)</td>
<td>–2.4 ± 0.5</td>
<td>1990–1999</td>
<td>Watson and Orr [2003]</td>
</tr>
<tr>
<td>OCMIP-2 (4 “best” models)</td>
<td>–2.2 ± 0.2</td>
<td>1990–1999</td>
<td>Matsumoto et al. [2004]</td>
</tr>
</tbody>
</table>

a Adjusted by 0.45 Pg C a⁻¹ to account for the outgassing of natural CO₂ that is driven by the carbon input by rivers.

b The estimate for a nominal year of 1995 would be less than 0.1 Pg C a⁻¹ smaller.


d These models were selected on the basis of their ability to simulate correctly, within the uncertainty of the data, the observed oceanic inventories and regional distributions of chlorofluorocarbon and bomb radiocarbon.

Global Carbon Budget for 2000-2005

Inventory changes adapted from Sabine et al., 2004
Tropical Pacific shows up as a significant sink for CO₂ despite the fact that net fluxes are out of the ocean and inventory estimates show a minimum near the equator.

An example of the differences between uptake and storage can be found in the Tropical Pacific.
Column inventory of anthropogenic CO$_2$ that has accumulated in the ocean between 1800 and 1994 (mol m$^{-2}$) based on $\Delta C^*$ approach

Mapped Inventory $= 106 \pm 17$ Pg C; Global Inventory $= 118 \pm 19$ Pg C
Shipboard Sampling for Ocean Carbon
Much of our understanding of the modern ocean carbon cycle was based on the GEOSECS program of the 1970s.

6,037 carbon samples with a DIC uncertainty $\sim 20$ µmol kg$^{-1}$
"...unless [inorganic carbon] measurements that are more accurate by an order of magnitude can be made, at least a decade will pass before direct confirmation of the model-based [fossil fuel CO₂ uptake] estimates will be obtained."

Broecker et al., *Science*, 206, p. 409, 1979
In the early 1990s the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the NOAA/OACES program joined forces to conduct a global survey of CO$_2$ in the oceans.

>70,000 sample locations; DIC ± 2 µmol kg$^{-1}$; TA ± 4 µmol kg$^{-1}$

Improved accuracy attributed to:

1. Refinement of coulometric DIC and SOMMA by K. Johnson
2. Development of CRMs by A. Dickson

http://cdiac.esd.ornl.gov/oceans/glodap/Glodap_home.htm
It was almost 20 years later before an improved anthropogenic $CO_2$ technique developed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Authors</th>
<th>CO$_2$ (Pg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972-78</td>
<td>GEOSECS</td>
<td>Brewer 1978</td>
<td>90 +/- ~40</td>
</tr>
<tr>
<td>1978</td>
<td>Brewer</td>
<td>Chen &amp; Millero 1979</td>
<td>90 +/- ~40</td>
</tr>
<tr>
<td>1979</td>
<td>Brewer</td>
<td>Gruber et al. 1996</td>
<td>118 +/- 19</td>
</tr>
<tr>
<td>1989-98</td>
<td>WOCE JGOFS</td>
<td></td>
<td>118 +/- 19</td>
</tr>
</tbody>
</table>

Atmospheric data from SIO and ESRL courtesy of P. Tans.
The WOCE/JGOFS period resulted in an unprecedented number of annual observations.

The CLIVAR/CO$_2$ program is making observations at 1/3 to 1/2 of the WOCE/JGOFS rate.

From Sabine et al., 2010
Moving beyond total carbon inventories...

Atmospheric data from SIO and ESRL courtesy of P. Tans
Comparison of the Change in Anthropogenic C Inventory over two decadal periods

Anthropogenic carbon inventory increases were higher at all latitudes over the last decade than the average increases between GEOSECS and WOCE.

The GEOSECS-WOCE changes were re-evaluated using the exact same techniques used for the WOCE-CLIVAR changes for these calculations.
Individual assessments of decadal carbon changes all show increases the patterns of change are complicated

Interim Results Have Shown:
1. On decadal scales, changes in ocean circulation can have a significant and sometimes dominant impact on carbon inventory changes.
2. The decadal patterns of anthropogenic carbon storage do not necessarily follow the long term storage pattern.

<table>
<thead>
<tr>
<th>#</th>
<th>Data from</th>
<th>Time period</th>
<th>Method</th>
<th>Reference</th>
<th>Year Range</th>
<th>Method Type</th>
</tr>
</thead>
</table>
I believe we are in a situation similar to the model evolution proposed by Corinne LeQuere a few years back.

Adapted from C. LeQuere
I believe we are in a situation similar to the model evolution proposed by Corinne LeQuere a few years back.
Figure 2  Anthropogenic carbon uptake rate from 1765 to 2008 (black solid line). The shaded area represents the error envelope (see Fig. 1 legend). Also shown are the decadal average uptake rates adopted by the IPCC fourth-assessment report (AR4) (blue circles; vertical error bars are 6 1 s.d. and horizontal error bars span the averaging period of years) and the atmospheric CO$_2$ mixing ratio used for the inversion (red dashed line).
**Feedbacks**

- **Land sink**
  - Increase in land sink from 2.4 to 1.5

- **Land-use change**
  - Increase in land-use change from 2.4 to 1.5

- **Fossil fuel and cement emissions**
  - Increase in fossil fuel and cement emissions from >5000 to 330

- **Atmosphere**
  - Increase in atmosphere from 590 to 204

- **River fluxes**
  - Increase in river fluxes from 0.2 to 0.5

- **River fluxes**
  - Increase in river fluxes from 0.2 to 0.5

- **PIC**
  - Increase in PIC from 0.1 to 0.3

- **POC + DOC**
  - Increase in POC + DOC from [3] to [25]

- **CaCO₃ formation**
  - Increase in CaCO₃ formation from 2.0 to 1.4

- **NPP**
  - Increase in NPP from 50 to 38.5

- **Respiration**
  - Increase in respiration from 1.9 to 1.5

- **Export**
  - Increase in export from 10 to 2

- **Remineralization**
  - Increase in remineralization from 3.85 to 5.0

- **DIC**
  - Increase in DIC from 120 to 140

- **CO₂ formation**
  - Increase in CO₂ formation from 0.4 to 0.2

- **Carbon overconsumption**
  - Increase in carbon overconsumption from 0.4 to 0.2

- **DOM recycling/export**
  - Increase in DOM recycling/export from 10 to 1.9

- **Denitrification**
  - Increase in denitrification from 0.1 to 0.1

- **Increased nitrogen fixation**
  - Increase in increased nitrogen fixation from 0.1 to 0.1

- **Reduced calcification**
  - Increase in reduced calcification from 0.1 to 0.1

- **Reduced particle ballast**
  - Increase in reduced particle ballast from 0.1 to 0.1

- **Increased stratification**
  - Increase in increased stratification from 0.1 to 0.1

- **Increased Southern Ocean winds**
  - Increase in increased Southern Ocean winds from 0.1 to 0.1

- **Reduced deep water formation**
  - Increase in reduced deep water formation from 0.1 to 0.1

- **Reduced upwelling**
  - Increase in reduced upwelling from 0.1 to 0.1

- **Increased carbonate dissolution**
  - Increase in increased carbonate dissolution from 0.1 to 0.1

**Sources**

- Sabine and Tanhua 2009
All Buffer Factors show a minimum where DIC=Alk

As CO$_2$ increases, North Pacific subtropical gyre waters are approaching the buffer minimum

Egleston et al. (GBC, 2010)
\[ \text{CO}_2^{(aq)} + \text{H}_2\text{O} + \text{CO}_3^{2-} \rightleftharpoons 2\text{HCO}_3^- \]
\[ \text{CO}_2^{(aq)} + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \]
Higher buffer factor means larger DIC increase for the same amount of CO$_2$ rise.
Higher buffer factor means larger DIC increase for the same amount of $CO_2$ rise.

25% drop in uptake.
Higher buffer factor means larger DIC increase for the same amount of CO$_2$ rise.

- Preindustrial
- Modern
- 2X CO$_2$
- 60% drop in uptake
Higher buffer factor means larger DIC increase for the same amount of CO$_2$ rise.
Global Carbon Budget for 2000-2005

- Atmosphere: [590 + 185]
- Ocean: [38,000 + 136]

Fossil Fuel & Cement Emissions
Volcanism
Plants & Soil [3800 -162 +161]
Fossil Organic Carbon [>6000 -304]
Geological Reservoirs

Land-Use Land Change sink
Respiration & Fires
NPP
Weathering
River outgassing
River export
River fluxes
Weathering

adapted from Sabine et al., 2004
Summary and Challenges

- Surface ocean observations and modeling are increasing and improving our ability to constrain the air-sea fluxes (uptake)

* This is still being done in an ad hoc manner and we will not be able to reach needed accuracy without better coordination and embracing new technologies

- Ocean interior measurements and modeling (inventories) compliment the uptake estimates and provide information on feedbacks

* These observations are personnel and infrastructure intensive thus they are not well supported with their current funding through research

- Coastal exchanges are not well understood

* Currently there is no coordinated effort to improve our understanding

- The above observing systems may also be able to address verification of ocean carbon capture and storage approaches

* However, the current programs are not optimized for this.